George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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Project Plan

For

Reusable Launch Vehicle (RLV) Focused Technology

ADVANCED SPACE TRANSPORTATION PROGRAM OFFICE (ASTP)

TD15

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Reusable Launch Vehicle Focused Technology Project Plan
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REUSABLE LAUNCH VEHICLE FOCUSED TECHNOLOGY PROJECT PLAN

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LIST OF ACRONYMS

AIT	Assembly, Integration, and Testing
ALT	Approach and Landing Tests
ASTP	Advanced Space Transportation Program
CADS	Calculated Air Data System
CDR	Critical Design Review
COTS	Commercial-Off-The-Shelf
DFRC	Dryden Flight Research Center
EAA	Enterprise Associate Administrator
ELV	Expendable Launch Vehicle
FDR	Final Design Review
FRF	Flight Readiness Firing
FTE	Full Time Equivalent
FY	Fiscal Year
GFE	Government Furnished Equipment
GFP	Government Furnished Property
GPMC	Governing Program Management Council
IA	Independent Assessment
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IPD	Integrated Powerhead Demonstration
IDR	Initial Design Review
IVHM	Integrated Vehicle Health Management
JSC	Johnson Space Center
KSC	Kennedy Space Center
NOA	New Obligational Authority
LaRC	Langley Research Center
MSFC	Marshall Space Flight Center
MOA	Memorandum of Agreement
NASA	National Aeronautics and Space Administration
NCAM	National Center for Advanced Manufacturing
NPD	NASA Program Directive
NPG	NASA Procedures and Guidelines
NRA	NASA Research Agreement
PCA	Program Commitment Agreement
PDE	Propellant Densification Experiment
PDR	Preliminary Design Review

PEM	Proton Exchange Membrane
PMC	Program Management Council
RLV	Reusable Launch Vehicle
SRR	System Requirements Review
SSC	Stennis Space Center
STPO	Space Transportation Program Office
TCS	Temperature Control System
TDRSS	Tracking and Data Relay Satellite System
TPS	Thermal Protection System
TBD	To Be Determined
ULCE	Ultra Low Cost Engine
VAB	Vertical Assembly Building

FOREWORD

This Project Plan describes the objectives, requirements, and planning for the Reusable Launch Vehicle Focused Technology Project. This plan is consistent with the objectives, requirements, and plans documented in the ASTP Program Plan, STD-TBD. This plan has been prepared in accordance with the *NASA Program and Project Management Processes and Requirements*, NPG 7120.5A, and is consistent with the *NASA Strategic Management Handbook* and *NASA Program/Project Management*, NPD 7120.4A. In addition, it follows the MSFC Lead Center Implementation Plan for Space Transportation System Development and Technology Programs.

I. INTRODUCTION

The RLV Focused Technologies will be developed under the auspices of the Advanced Space Transportation Program (ASTP). These technologies will address critical component, sub-system, and system level technologies requirements in support of the development of a fully reusable launch vehicle.

This RLV Focused Propulsion Technologies Project Plan provides information for the organizational structure, responsibilities, procedures, process, and resources for implementing the development of material and component technologies defined as part of the ASTP. This plan determines the design process required to meet technical requirements and the needs of our customers. This integrated technology project plan is designed such that technical content and tasks can be added or deleted as required without changing the basic guidelines stated by the plan.

The Project Manager is responsible for maintenance of this plan. Any proposed revision to this plan is submitted to the Project Manager for authorization and subsequent incorporation after approval per ISO-STP-01.

II. OBJECTIVES

The RLV Focused Technology Project is chartered to enable airframe, power, thermal protection system (TPS), and propulsion technologies that increase the reliability and performance of reusable space transportation systems with the goal of enabling the development of the second generation reusable launch vehicle to greatly reduce the cost of access to space. The RLV Focused Technology Project is to coordinate technology development with other NASA programs to assure that the technologies included in the Project have maximum application to, and synergy with, those technologies developed under the X-33, X-34, and other NASA, DOD, and commercial RLV activities.

The RLV-Focused Technology project was initiated to support required technologies for meeting the second generation RLV goals (Goal 9). Specifically, this project will develop and demonstrate technologies hat will enable U.S. industry to reduce costs by an order of magnitude ($1,000 per pound cost to NASA) and increase safety by 2 orders of magnitude (loss of crew probability less than 1 in 10,000 missions) within 10 years. Activities will support a competitive down-selection by 2005.

The project will focus on four areas of development. Within each of these task areas, there will be multiple sub-tasks identified.

- Airframe/Primary Structure

- Power
- Thermal Protection Systems
- Propulsion
  - Advanced Components
  - Propellant Densification Experiment
  - Advanced System/Cycle Demonstration

III. CUSTOMER DEFINITION AND ADVOCACY

The RLV Focused Technology Project is aligned within MSFC's Advanced Space Program Office and NASA's Office of Aero-Space Technology (OAT) Enterprise, and supports the strategic goals of OAT's third pillar, Access to Space. Specific Access to Space Pillar goals are to achieve a ten-fold reduction in the cost of placing payloads into low-Earth orbit in the next decade and an additional ten-fold cost reduction in the decade beyond.

The primary customer of the RLV Focused Technology Project is the Office of Aero-Space Technology Enterprise. Customer advocacy will be achieved by a number of approaches including instituting cooperative arrangements with government agencies and industry partners who have synergistic goals. These agreements will provide for the timely release of data that may be beneficial to current and future launch vehicle development programs. The RLV Focused Technology Project will conduct periodic technology exhibitions to highlight ongoing technology efforts. Customer participation in establishment, review, and approval of requirements and in design reviews will be encouraged.

The RLV Focused Technology customer base also includes:

- Universities/Academia
- Human Exploration and Development of Space Enterprise
- Department of Defense (DoD)
- Industry

IV. PROJECT AUTHORITY

The *NASA Strategic Plan* and the *NASA Strategic Management Handbook* assign to MSFC the Lead Center responsibility for Space Transportation Systems development. This assignment includes Lead Center responsibility for the ASTP Program of which the RLV Focused Technology Project is a part. The RLV Focused Technology Project Manager is responsible for project implementation and management. The RLV Focused Technology Project has direct commitments with MSFC and other NASA centers. The MSFC PMC is responsible for oversight of the RLV Focused Technology Project.

V. MANAGEMENT

A. Organization and Responsibilities

1. NASA Headquarters

NASA's Office of Aero-Space Technology (OAT) Enterprise is responsible for the RLV Focused Technology Project.

2. Field Centers

The field centers involved in the RLV Focused Technology Project include: Marshall Space Flight Center, Ames Research Center, Glenn Research Center, and Langley Research Center. The involvement of each center is described below:

a. George C. Marshall Space Flight Center (MSFC)

The project is managed under the MSFC Space Transportation Directorate's (STD) ASTP Program Office. The Project Office consists of a Project Manager, a lead systems engineer, and a part-time resources person. MSFC will be responsible for the overall management for all of the tasks of this project. In addition, MSFC will contribute excellence in the area of highly-reusable, high-thrust-to-weight propulsion system technologies.

b. Glenn Research Center (GRC)

Glenn Research Center (GRC) is responsible for providing the expertise and management of those tasks focused on the advancements of power systems as well as contributing expertise in propellant Densification and propulsion technologies.

c. Ames Research Center (ARC)

Ames Research Center (ARC) is responsible for the design and demonstration of high-temperature ceramic thermal protection system technologies as funded within the project.

d. Langley Research Center (LaRC)

Langley Research Center (LaRC) will provide management, as delegated by the MSFC Project Manager, of those tasks in the areas of airframe, TPS, and power. LaRC will perform technology development in the area of primary structures and airframe technologies.

e. Stennis Space Center (SSC)

Stennis Space Center (SSC) will be responsible for test and validation of large propulsion components and propulsion demonstrator testing.

B. Responsibilities

The tasks identified within this project will be managed out of the MSFC ASTP office. Teams will be formed as required at the appropriate centers and industries to support the development of each task. Contractor support will be used with the permission of the Project Manager. The teams are empowered to develop the test and flight articles within the guidelines established in this project plan.

1. Program Management (Level II).

Overall Program Management is provided by the Advanced Space Transportation Programs Office.

2. Project Management (Level III).

The Project Manager is assigned by MSFC's ASTP office and reports to the ASTP Program Manager (Level II). The Project Manager is responsible for developing an approach to meet the objectives established by the ASTP Program Manager; developing lower level project constraints such as budget, resources and schedule; and implementation planning that coordinates NASA and contractor assets.

The products of the Project Manager are:

- **Project Plan**. The Project Plan shall be written in accordance with NPG-7120.5A
- **Integrated Project Schedule**. The Integrated Project Schedule shall be developed using Microsoft Project and will contain all tasks identified by the appropriate teams and the Project Management. The tasks shall be logically linked with the critical path identified. The project schedule shall contain detailed schedules of all project elements and shall be updated in a timely manner. The project schedule shall contain the baseline schedule and deviations from the baseline. The Project Manager must approve changes to the baseline schedule.
- **Resource Allocations** (POP inputs). The Resource Allocations contain estimates of budget requirements and manpower requirements. This report indicates when budgeted funds will be obligated and costed as well as the cost of in-house manpower and manpower phasing. The Project Manager is assisted by a business manager who is assigned by the ASTP management. The Business Manager's primary responsibility is to assure that all procurements are planned and purchased in time to support the project schedule. The Business Manager shall work with the PDTs to evaluate procurement needs and schedule; track expenditures; and reports progress and issues to the Project Manager.

- **Collaborative Work Commitments** (CWC). The Project Manager will develop CWCs per MSFC-P03.1-C01 The Project Manager will be assisted by the Lead Systems Engineer. CWCs are controlled by the Project Manager and held as a quality record in accordance with MSFC-P16.1 for 6 months after completion of the task.

3. Engineering Management (Level IV).

The Lead Systems Engineer is assigned by the ASTP Program Manager and reports to the Project Manager. The Lead Systems Engineer is responsible to the project for ensuring that all engineering aspects of funded tasks, including in-house, other centers and contractor responsibilities are accomplished within the technical requirements and cost and schedule restraints.

The products of the Lead Systems Engineer are:

- CWCs that support project schedule.
- Level 4 directives, releasing drawings, documentation and change control documentation.
- COTR support and documentation for contracts that support the project tasks.
- Design review agendas, review team coordination, and pre-board disposition.

MSFC Task Managers or Principal Investigators (PIs) will be assigned for each task funded within the project. Their role will be technical with regard to the nature of the work being conducted in the task. Additional information on specific task management and Product Development Teams are given in the task specific sections of this document.

C. Special Boards and Committees

The Project Manager shall schedule independent status reviews as required with technical experts not associated with the development activity. Each PI will be responsible for presenting the status and plans for their task. These reviews will assess the progress of all tasks within the project with regard to progress and issues. A logical result of this review will be guidance on the continuation, termination, or modification of the tasks contained within the project. The Project Manager will be responsible for the meeting agenda and overall coordination with the PIs for the review items.

D. Management Support Systems

The Project Manager is assisted by a schedule development expert. This support will coordinate development of the project's integrated schedule with input from the Lead Systems Engineer, and each Task Manager. The Project Manager is also supported by the Business Manager.

E. Management Information Systems

The MSFC Online Project Management System (OPMS) will be used to track the technical and fiscal progress of each propulsion related task within the project. All plans, reports, schedules, design documentation, etc., shall reside on the OPMS. Only those records contained on the OPMS will be considered official and current. The PIs shall be responsible for maintaining the content of the OPMS for their task. Monthly status reports will be entered into the OPMS by each PI.

The MSFC managed propulsion task schedules are in the Microsoft Project format and are maintained in MSFC Online Management System under the RLV Focused Propulsion RTIP Wing. Individual schedules within this document will defer to the online consolidated schedule should there be a conflict in the two documents.

The Langley Management Information System will be used to track the technical and fiscal progress of airframe and structures tasks within the project with the exception of two tasks. Glen Research Center will manage and track the progress of the PEM fuel cell task, and Ames Research Center will manage and track the progress of the Advanced Blanket Thermal Protection System task. All plans, reports, schedules, design documentation, etc., will be maintained by the Langley Space Transportation Program Office. The Langley STPO will maintain and provide to the MSFC RLV Focused Project Management monthly status reports on all tasks.

All LaRC managed Airframe, TPS, and Power task are maintained in the Langley Management Information System. Individual schedules within this document will defer to the online consolidated schedule should there be a conflict in the two documents.

VI. TECHNICAL SUMMARY

Each task contained within the RLV Focused Airframe Systems Technologies Project of the Advanced Reusable Technology Project is described in the following pages of this document. The basic structure of this plan was developed to enable modification, addition, or deletion of technical content without effecting the overall project plan. The project currently consists of five technology elements/areas described below. More details can be found in the appendices.

- Composite Tank and Structures Technologies
- Thermal Structures and Hot Structures Technologies
- X-33 Ground Based IR Imaging Aeroheating Experiment
- PEM Fuel Cell, and
- Propulsion technologies
    - Advanced Components
    - Advanced Propulsion System/Cycle Demonstrations

A. Composite Tank and Structures Technologies

Vehicle studies show that polymeric composite cryogenic tanks offer significant weight reduction for Single-Stage-To-Orbit (SSTO) RLV. However, to date, large scale composite liquid hydrogen (LH2) and liquid oxygen (LOX) tanks have never been successfully demonstrated. The major challenges which remain to realizing the promise of PMC cryogenic LH2 and LOX tanks include validation of compatible materials systems and processes, fabrication and joining of large scale articles, and demonstrated thermal-structural performance. Tasks proposed in this technology element address these challenges.

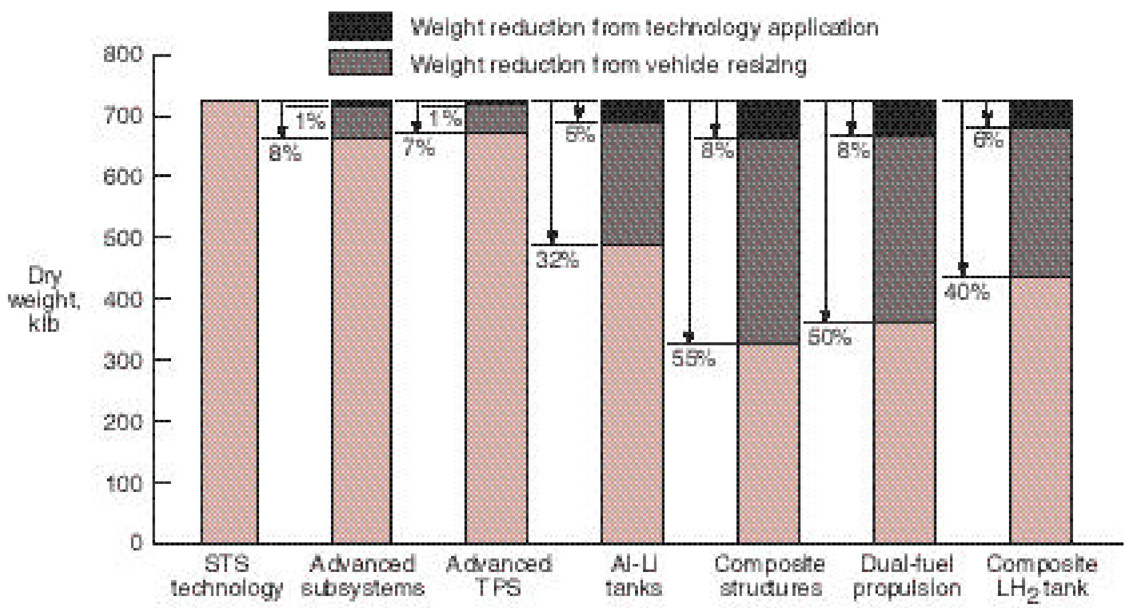

Figure VI-1. Effect on Single-Stage to Orbit vehicle dry weight through incorporation of advanced technologies.

The Composite Tank and Structures Technologies element of the project includes four tasks which focus on the development and demonstration of composite materials and structures for reusable launch vehicles (RLV). The four tasks included in this element are summarized below:

1. Nonautoclave Processing, LOX Compatible Composites, and Cryogenic Insulation for Vehicle Thermal Structural Systems (Appendix 1)

Sizes of cryogenic tanks for current SSTO designs, carrying 25,000 lbs payload to low earth orbit, exceed 50 ft. in length and 20 ft. in width. Autoclaves large enough to cure composite structures of this size do not currently exist. Any near term decision to build an RLV of this class using composite cryogenic tanks will therefore be highly dependent upon our understanding of nonautoclave processes for fabrication and joining of large scale composite parts.

Through this task, an updated database of nonautoclave processes and their respective composites will be developed. This task will pursue two approaches for the development of nonautoclave processable composite materials and process technologies for RLV. One approach will explore the development of materials and fabrication processes for electron-beam curable polymeric composites. The other approach will examine derivatives of materials and processes developed under NASA Aeronautics Programs, including NASP, High Speed Research Program, and Advanced Composites Technology Program. Techniques which have shown promise in these programs, including advanced tow placement (ATP) , resin transfer molding and resin film infusion (RTM/RFI), will be further explored for development of materials systems for RLV. This work will be performed at the NASA Langley and Glen Research Centers, the Marshall Space Flight Center (MSFC), Oak Ridge National Laboratory (ORNL), Lockheed Martin Skunk Works (LMSW), Northrop Grumman, Applied Polymeric Composites, Rensselaer Polytechnic Institute, Science Research Labs (SRL), Boeing, and the Airforce Research Laboratory.

In addition to nonautoclave processing of composite materials, LOX compatible resin systems and improved cryogenic insulation will be worked under this task.

2. Joining Technology (Appendix 2)

This task will develop design and analysis tools and a series of innovative joint design concepts for both cryogenic tanks and dry structure. Effective joint designs will enable development of large cryogenic tanks and dry structure that can be fabricated in existing autoclave facilities. Joint designs are needed to significantly reduce structural weight and fabrication costs and greatly increase fatigue resistance and structural reliability. For large structures, efficient and reliable joint designs could significantly reduce fabrication costs by eliminating the need for an autoclave. Bolted joint designs are mature, but result in a significant weight penalty and are difficult to seal against leakage of LH2. Bonded joint designs are less mature than bolted joint designs, but are weight efficient and are not as difficult to seal as bolted joints. However, the reliability of bonded joints in cryogenic tanks must be demonstrated. Fiber-optic sensors and health monitoring technology are needed for structural joints to provide a global health monitoring system for the vehicle structure.

3. Cryogenic Tank Panel, Sub-component Development and Integrated Structures TPS Test (Appendix 3)

The lack of sufficient understanding of the thermal-structural interactions of the RLV thermal protection system with the cryogenic tank that supports it is a significant risk because of the critical need to ensure the TPS will protect the PMC structure. RLV cryogenic tanks are the largest component of vehicle dry weight and are the majority of the primary structure. Thus, to minimize vehicle dry weight and cost and assure the performance of the integrated cryotank TPS system, validation of our capability to design an integrated system and predict the performance and failure modes of the integrated system in a controlled test environment is required.

This task investigates cryogenic tank structural configurations (membrane, semi-conformal, and conformal tanks), wall constructions (variations of sandwich and stiffened, lined and unlined), cryogenic insulation concepts, and TPS support structure and attachment concepts on a consistent basis to determine the weight, integration, and operational characteristics. Existing concepts are modified and new concepts are defined, analytical studies are performed, and the most attractive concepts are determined based on analyses and tests. Full-scale subcomponents of selected concepts are fabricated and thermal-mechanically tested to validate the designs. Current fabrication processes at MSFC and at LaRC are used in a collaborative effort to manufacture advanced integrated tank test specimens for demonstration and testing. These specimens will be tested at LaRC under static and cyclic vehicle operational conditions to verify the thermal and structural characteristics, and fabrication technology utilized in the integrated concepts.

4. Electron-beam Curing of Composite Cryogenic Propellant Tanks (Appendix 4)

Critical processes required to validate the ability to produce large-scale composite tanks still lack the maturity to produce cryotankage of the scale and reliability required for RLV applications. Out –of-autoclave methods carry the potential of being able to produce these components without the vast expendetures required for an autoclave of the required size and capability. This task is to develop and demonstrate the technology for out-of-autoclave fabrication of a composite cryotank using electron-beam curing.

To best validate the capabilities to develop and demonstrate the technology for fabricating a cryotank through E-beam curing the test article will be designed with inverted domes and unique joints to better explore the limitations of the technology.

A key goal will be to determine the structural strength at cryogenic conditions of a spliced woven Y-joint for the dual cylinder E-beam test tank. The Y-joints are located along the intersection between the dual cylinders of the E-beam test tank and have also been referred to as the double cylinder tank barrel-to-barrel joints.

5. National Center for Advanced Manufacturing (Appendix 5)

The National Aeronautics and Space Administration (NASA) has established the National Center for Advanced Manufacturing (NCAM). The NCAM has been created to address the research and technology development needs for manufacturing the next generation of reusable space transportation systems while also building a future manufacturing technology base for NASA and industry. The mission of the NCAM is to establish partnerships involving NASA, government agencies, states, universities and industry, that will develop manufacturing technologies enabling new launch vehicle and propulsion systems with orders of magnitude improvements in safety, cost and reliability.

Conceptual designs for reusable space transportation systems, including the Lockheed Martin VentureStar require unprecedented very large composite structures to achieve the necessary mass fraction for a single stage to orbit vehicle. The ability to effectively reduce system costs and development cycle times will rely on breakthroughs in the engineering environment. Furthermore, new education and training in the operations of technologically advanced manufacturing systems is critical to revolutionary product development. Current research has identified that the advanced manufacturing processes, and the level of performance of engineering tools are not available today for production of these very complex structures.

Intense global competition in the launch vehicle and aircraft businesses are requiring changes in the way U. S. aerospace industry operates to become globally competitive. In less than ten years, the U. S. has gone from dominating the launch vehicle market to owning less than 40%. NASA's interest and sponsorship of the NCAM is in direct support of helping the U. S. compete internationally.

Involving education is critical to the success of this endeavor. Development of revolutionary engineering tools will require expanding the scope of current educational achievement. The NCAM will support universities in exploratory development and participatory efforts in emerging educational technologies to provide knowledge and skills for the next generation technological workforce.

B. Thermal Structures and Hot Structures Technologies (Appendix 6)

Areas critical to the development of lightweight robust thermal protection systems for RLV are addressed in this technology element: 1) Metallic Thermal Protection Systems (TPS); 2) Advanced Durable Blanket Technology, and; 3) Integrated Hot Structure. The large maintenance burden of the Reusable Surface Insulation (RSI) ceramic tile TPS for the Shuttle (estimated between 40,000 and 70,000 hr/flight) is one of the principal reasons for seeking alternative approaches for acreage TPS on RLV. Metallic TPS is baselined in the X-33 RLV program. Metallic thermal protection systems (TPS) have the potential to be more robust and to require significantly less maintenance than current ceramic tile and blanket TPS. With improved structural integration, materials, insulation, and attachments, metallic TPS can also offer reduced weight, improved vehicle performance through higher TPS temperatures, and all-weather operation. Another approach, aimed at reducing vehicle life cycle costs, is conformable reusable insulation (CRI). These are ceramic blanket panels which are larger than the RSI tiles, less expensive to manufacture, and have lower maintenance unit costs.

The thermal limits of metallic and CRI TPS restrict the application of these TPS. Areas of the vehicle, such as leading edges and control surfaces, which experience higher thermal loads require a different approach, such as hot structures, to reduce overall vehicle weight and maintenance. Hot structures offer the potential to significantly reduce the TPS requirement for an RLV and thereby reduce vehicle weight and maintenance. However, to date, many of the hot structures have been costly to manufacture and the material system characteristics do not support high load bearing structures. In this activity, Northrop Grumman will explore the development of a structurally integrated high temperature wing design for an RLV. The wing structure will integrate a polymer matrix composite (PMC) primary structure with a strain-compliant Ceramic Matrix Composite (CMC) Hot Structure through co-processing and explore the use of 3D textiles woven preform technology with resin film infusion to reduce manufacturing cost.

Tasks included in this technology element:

- Constituents and Fabrication Techniques for Metallic TPS
- Advanced Durable Blanket Technology
- High Temperature Integrated Structures

C. X-33 Ground Based IR Imaging Aeroheating Experiment (Appendix 7)

The validation of experimental and computational predictive techniques is essential for the success of single-stage-to-orbit technology and future space transportation technology development. Conservatism in design must be eliminated or minimized to enable low cost space transportation. Outer mold lines (OML) must provide the aerodynamic performance to meet mission objectives with the minimum surface area (translates to weight) possible. The aerodynamic and aeroheating disciplines are the drivers for vehicle design and provide critical inputs to other disciplines such as control system design, materials, and structures. Aerodynamic and aeroheating data provide the input for thermal protection system (TPS) material selection and sizing, which must represent the minimum weight to ensure survivability and reusability. For autonomous landing vehicles, the aerodynamic performance and margins must be known precisely throughout the entire flight trajectory. To achieve these goals of optimum design of future RLV's, reduced vehicle design cycle time, and to enhance U.S. space launch competitiveness, designers must have highly accurate, calibrated and validated tools for prediction of aerodynamic performance and aeroheating characteristics. Aerothermodynamic flight data provides the ultimate means for tool validation. Once validated, these tools may be used with confidence for the next generation of RLV's and vehicles such as military spaceplanes, and Shuttle Orbiters.

D. PEM Fuel Cell (Appendix 8)

The Proton Exchange Membrane (PEM) Fuel Cell task is managed by the NASA Glen Research Center. This task is a 26-month program to develop PEM fuel cell technology for potential RLV applications. Compared to the present alkaline fuel cell technology (used on the Shuttle), the PEM technology offers the following advantages:

1. Lower cost with significant future cost reductions
2. Lower maintenance and longer life (10,000 hours v.s. 2000 hours)
3. More fuel efficient (approximately 10% less fuel for same power level)
4. Reduced weight (approximately 50% more power for same weight)
5. Can use less pure propellant-grade reactants

E. Propulsion – Advanced Component Technologies

Propulsion systems studies show that the most significant area of improvement for chemical propulsion systems are in the areas of improved thrust-to-weight derived from the integration of advanced materials and from the improvement of turbopump efficiency, Integration of high strength to weight materials allow for increased safety margins in critical components that can prove catastrophic if a failure occurs. Increased efficiency in the turbopumps can also increase the margins through a decrease in operating speeds or my allowing for fewer pump stages to produce the same work. The Advanced Propulsion Components Technologies element of the project includes eight tasks which focus on the development and demonstration of composite materials and advanced design tools for reusable launch vehicles (RLV) propulsion systems. The eight tasks included in this element are summarized below:

1. Lightweight Composite Ramp Technology Task (Appendix 9)

Metallic nozzles and the required supporting hardware required to cool the inner wall of the nozzle of a traditional liquid rocket engine have accounted for a very high percentage of the propulsion system weight. This trait is common regardless of the nozzle configuration, i.e., bell or aerospike ramp. The integration of advanced ceramics into nozzle fabrication offers a unique, but extremely challenging, opportunity to reduce the weight of the nozzle significantly. This high-temperature tolerant material may also eliminate the requirement to actively cool the nozzle ramp of the Aerospike during the critical descent where currently projected heat loads are the most severe.

The proposed task is distinctly different, but builds upon, the baseline funded RLV composite nozzle task. Currently proposed material system concepts for the aerospike cooled composite nozzle ramp base program are challenged to meet the weight goal of 2 pounds/ft2. Due to the development schedule imposed upon the baseline cooled composite nozzle ramp task, certain advanced, innovative concepts will not be selected as they lack the maturity necessary to meet the aggressive baseline development plan delivery schedule. The technological progression and sub-scale demonstration of these concepts towards the RLV performance goals is expected to provide critical and potentially enabling input into the RLV go/no go decision - even though the program outlined here does not meet the large scale test article test demonstration requirement currently imposed by the baseline RLV program. These innovative concepts however, offer significant potential advantages in the critical areas of performance, cost, reliability and inspectability.

2. Lightweight, Long Life Thrust Cell (Appendix 10)

The overall objective of this program is to develop lightweight alternatives for thrust cells that are exposed to extreme hot gas environments. Currently, thrust cells for the Reusable Launch Vehicle (RLV) program's Venturestar and X-33 engines comprise approximately 25% of the engine weight, and their hot gas walls (HGW) are exposed to high temperature combustion products that can limit the thrust cell's life. Reducing weight while overcoming thermal issues can benefit these launch vehicle programs, as well as the engines being developed for the HEDS (Human Exploration & Development of Space) program.

This task plan outlines the activities that will be performed to address the development of lightweight, long life alternatives to the current thrust cell designs. These tasks were defined to address material, design, and fabrication issues, and to perform appropriate analysis and testing for developing and verifying concepts. Schedule, budget, and personnel aspects for managing this program are also outlined.

3. Copper-Chrome – Niobium (Cu-8 Cr-4) Nb RLV Thrust Cell Liner Program (Appendix 11)

The Reusable Launch Vehicle (RLV) will require new materials in order to achieve its goals of decreased launch costs and increased reliability and durability. One area of particular concern is the thrust cell of the aerospike engine. Rocketdyne Division of Boeing has baselined the new NASA GRC developed Cu-8 Cr-4 Nb (Cu-8 at.% Cr-4 at.% Nb) alloy for use in the RLV engine thrust cell liner. Utilization of the current Space Shuttle Main Engine (SSME) liner material, NARloy-Z (Cu-3 wt.% Ag-0.5 wt.% Zr), could severely limit the life of the engines and may not provide the necessary capabilities to achieve the payload goals of the RLV program. NARloy-Z has also demonstrated two major problems, blanching and the failure of the chamber liner wall over cooling channels known as the “dog house” failure. Conditions in the RLV thrust cell could cause similar failures.

The task will consist of two main areas: development of a design level database for use in the RLV program and analysis of the material to better understand the microstructure-properties relationship. The understanding can be used to improve materials processing and properties as well as allow better modeling and life prediction in the future. As a consequence of the database development, the new powder supplier, Crucible Research, will be qualified as a supplier of Cu-8 Cr-4 Nb powder to the RLV program.

4. Light-Weight Gas-Generator Combustor Assembly (Appendix 12)

The overall objective of this task is to develop and demonstrate uncooled, hot gas impermeable ceramic composite structures, and deliver a full-scale, lightweight design of a gas generator combustor assembly. The effort is led by NASA GRC teamed with MSFC and Rocketdyne. Ceramic composite development tasks are heavily leveraged from NASA GRC aeronautics and ground-based propulsion programs. By simultaneously addressing the unique processing and properties of ceramic matrix composites and the design requirements of a gas generator combustor assembly, it is expected that a final lightweight, simple design will be delivered that would not be possible with other materials. The demonstration of hot gas impermeable ceramic composite structures would also be applicable to other RLV components such as the thrust cells and nozzle ramp.

This task plan outlines the activities that will be performed to address the development of lightweight, long life alternatives to the current gas generator assembly design. These tasks were defined to address material, design, and fabrication issues, and to perform appropriate analysis and testing for developing and verifying concepts.

5. Polymer Matrix Composite Lines, Valves and Ducts (Appendix 13)

The Access to Space Study identified the requirement for lightweight structures to achieve orbit with a single stage vehicle. The use of composite components will partially fulfill that requirement. The purpose of this task is to extend previous efforts with polymer matrix composite (PMC) lines, and develop additional technology for application to PMC valve housings. This project plan identifies activities, deliverables, participants, and key milestones for this task. This plan will be updated significantly during the project planning phase of this task.

MSFC will fabricate lines and valve housings under this project for testing in LH2 and LOX environments. Several key technologies will be demonstrated in the ducts. These include scalability, composite flanges, flange sealing, ability to build complex geometries, one piece fabrication, reparability, and low cost tooling. A composite valve housing as a replacement unit for an existing valve design will be designed and fabricated by a selected valve supplier, and will be tested at MSFC. Additional lines will be fabricated using alternate materials and processing methods, including electron-beam curing coordinated through Oak Ridge National Laboratory (ORNL) and solvent-assisted resin transfer molding (RTM) processing coordinated through GRC.

The materials used in this project will be characterized to obtain mechanical, physical, and damage tolerance properties. Repair and inspection methodologies will be developed for the lines.

6. High Head Unshrouded Impeller Technology (Appendix 14)

Marshall Space Flight Center (MSFC) has been actively involved in the design and testing of high performance pump elements since 1988. Jointly with Rocketdyne (and other entities) we designed and tested an advanced, high head shrouded impeller designed to allow a two stage fuel pump for the now canceled Space Transportation Main Engine (STME). This would have led to lower manufacturing cost and increased engine thrust-to-weight (T/W) ratio over the baseline 3-stage design. The Reusable Launch Vehicle (RLV) will require higher T/W ratio engines than currently available.

One of the key technologies that will enable significant improvements in T/W ratio is advanced unshrouded impeller technology. Unshrouded impellers have been used in rocket engines in the past primarily because they can be manufactured less expensively than shrouded impellers. However, unshrouded impellers also have a structural advantage over shrouded impellers. The use of unshrouded impellers allows for higher tip speeds and, hence, greater pressure rise per pump stage (increased stage loading), resulting in the reduction of turbopump size and weight.

Weight Savings Potential for SSME ATP HPFTP

	Shrouded	Unshrouded
Pump efficiency (%)	78.6	76.3
Pump horsepower	75670	78600
Impeller tip speed (ft/sec)	1890	2321
Head coefficient	.558	.552
Stage loading (feet of head)	61145	92390
Pump stages	3	2
Turbopump weight (pounds)	990	490

The table above illustrates the potential benefits of the increased stage loading (possible with unshrouded impellers) for the Space Shuttle Main Engine (SSME) Alternate Turbopump (ATP) high-pressure fuel turbopump (HPFTP). Note that there is a potential weight savings of 490 pounds to the ATP HPFTP if advanced unshrouded impellers are used.

Marshall Space Flight Center has been working on developing this technology for a potential upgrade to the SSME. Extensive design parametrics have been performed on impellers designed to meet the SSME HPFTP pumping requirements. This effort has resulted in an impeller design that does meet the pumping requirements for a two stage SSME HPFTP. The resulting impeller design's performance will be verified at MSFC's pump test equipment (PTE) facility in a impeller test rig especially designed to facilitate testing of unshrouded impellers.

7. Turbine Performance Optimization Technology Task (Appendix 15)

The Reusable Launch Vehicle (RLV) requires a high value of specific impulse (I_{sp}) and a high thrust to weight ratio. These requirements have necessitated compact,

Weight Savings Potential for the SSME ATP HPFTP

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high power turbine designs. Turbine power is produced through a combination of its mass flow rate and work per pound of fluid. The RLV engine is a gas generator cycle where propellant is tapped off of the main engine flow to provide the drive gas for the turbine. At the exit of the turbine, the drive gas is dumped overboard and does not contribute to engine thrust. Therefore, for a gas generator cycle, the mass flow rate through the turbine is a direct loss to engine I_{sp} and must be minimized, and power must be produced predominately through high work.

To obtain high work, the available energy of the gas must be increased, or the turbine must extract energy from the gas more efficiently. This task addresses the second option. If the turbine work is held constant, a reduction in turbine temperature is directly proportional to the efficiency increase. The current total-to-static efficiency of the RLV fuel turbine is 58%, leaving a large opportunity for improvement. An increase of 8 points in turbine efficiency would result in an approximate reduction of 275° R (with an approximate inlet temperature of 1825° R) and the possibility of an uncooled metal turbine. Cooler temperatures also increase margins for the metal housings. The mass flow rate through the turbine is currently 64.4 lbm/sec. For every 4 lbm/sec reduction in mass flow rate, engine I_{sp} is increased by 1 sec. If efficiency is increased by 8 points, mass flow rate can be reduced by approximately 10 percent, or 6 lbm/sec, and engine I_{sp} is increased by approximately 1.5 seconds. As a secondary benefit, reducing turbine mass flow rate improves the mixture ratio of the modular thruster, thereby increasing engine I_{sp}. One second of I_{sp} is equivalent to 1500 lbm of payload or 168,00 lbm of gross lift-off weight.

8. Metal Matrix Composite Components - Turbo Demo (Appendix 16)

The objective of this task is to demonstrate and validate the utilization of an advanced material in the fabrication of high-pressure structural housings that will provide significant engine weight decrease. The Revolutionary Reusable Turbopump Technology (RRTT) demonstrator is a high-pressure, oxygen rich turbine driven pump. This task will use this pump to demonstrate the integration of Metal Matrix Composites into the system by replacing two of the major castings of the RRTT with alternate components fabricated from Cu-based MMCs. While the Cu-based MMC is required for the oxygen rich environment of RRTT, Al-based MMCs will also be addressed at a reduced level to provide the designer with the option of using the Al-based components for an even greater reduction in engine weight where appropriate.

A continuous fiber reinforced MMC will be used to replace the existing turbine and pump inlet housings on the RRTT to demonstrate the weight reduction benefits. MMC was selected for both the hot GOX and cryogenic LOX housings after considering competing lightweight materials, such as silicon nitride, polymer matrix composites, and ceramic matrix composites. The main discriminators in favor of MMC are the recent industrial demonstrations of large, complex MMC hardware, the availability of manufacturing facilities capable of fabricating RLV scale housings, and the inherent ox-rich environmental capability for long0duration use without coatings or claddings. Despite these recent advances, the current TRL for MMC TPA housings is only three. This task will bring the TRL for MMC to the required level.

After the candidate alloy and fibers are selected based on key screening criteria such as ox-compatibility, specific strength and producibility. Additional testing will be performed to assess H2 compatibility to enable a wider range of future applications. With the selected MMC, scale-up of the processing technique for large-scale TPA housings will be demonstrated, leading to proof testing of representative components. Housings will then be fabricated and tested for subsequent assembly in the RRTT. Also, in parallel, a new ox-rich gas generator will be designed and fabricated by Rocketdyne and tested to allow hot-fire testing of the RRTT with the new lightweight housings installed.

F. Propulsion – Advanced System/Cycle Demonstrations

The five Space Transportation Architecture Study contractors were all in agreement in saying that the single greatest challenge in going forward with a new second generation RLV was the availability of a highly reliable and low-cost propulsion system. One pathway toward lowering the cost of propulsion systems for access to space is to produce a very low cost booster engine that would begin as an expendable engine with growth paths to a reusable for Reusable First Stage applications. The second pathway is to build on the vast industry experience with the Space Shuttle Main Engine and evolve it to the next step in staged combustion engine technology. A full-flow staged combustion engine based on the SSME heritage and database could produce SSME performance with a significant increase in reliability and a significant decrease in per unit cost. The RLV Focused Technology Project is currently pursuing substantial efforts in both of these areas in large scale demonstrators. The two tasks included in this element are summarized below:

1. 650 KLBF LO2/LH2 Engine Demonstration (Appendix 17)

In the last twenty five (25) years, only three 1-02/1-1-12 large booster engines have been developed by the free economy nations. All of these designs were driven by performance rather than cost or schedule. To achieve the high performance goals, pushing the limits of technology resulting in expensive technology and manufacturing development. The resulting engine designs were both complex and extremely costly to manufacture. While continuous efforts have been underway in the United States to reduce existing engine costs through redesign of key components, these effort have yet not resulted in any significant reduction in overall engine cost.

TRW and NASA are performing this two phase task under a Cooperative Agreement. TRW will demonstrate an Ultra Low Cost Engine (ULCE) operating at 650,00 LIBF thrust. This engine will include GH2 powered Turbopumps, Propellant Valves, Injector Assembly, and an Ablative Combustion Chamber Assembly. The testing of this engine will fully demonstrate the capability of a pintle injector, ablative lined engine to achieve high performance and combustion stability while burning L02/H2 propellants at 700 psia chamber pressure. TRW proposes to use the engine that was completed in 1996 using TRW, Allied Signal Aerospace, and McDonnell Douglas Aerospace funds. TRW plans to use existing materials and engine parts to prepare a second combustion chamber and nozzle assembly with film cooling. The TRW engine will be ready to mount on the NASA SSC test stand with the addition of interface plumbing and a thrust structure that are compatible with both the SSC E-1 test stand and the TRW engine. Included in this revised proposal are the TRW costs and the value of the Pump Fed Engine Assembly.

2. Integrated Powerhead Demonstration (Appendix 18)

Propulsion systems on current U. S. spacelift systems achieve high reliability only after extensive pre-flight inspections and tests. These propulsion systems require significant ground and inflight support that increases not only the cost of support equipment, but the operational costs due to maintenance and inspection of the support equipment. Launch system operational effectiveness is hampered by propulsion system high sensitivity to contamination and environmental conditions such as humidity and plume recirculation. As a result, costs are high and launch responsiveness cannot be achieved.

Reliability and life can be increased by incorporating new materials and by using alternate power cycles to reduce the severity of engine component environments. Launch vehicle life cycle costs can also be reduced by increasing the reliability of the propulsion system through application of built-in test and health management systems. For both expendable and reusable propulsion systems, operational and equipment costs can be reduced by eliminating propulsion system services that add to ground and vehicle support equipment. The least reliable and life-limiting components of current expendable and reusable hydrogen/oxygen liquid rocket engines are the high-pressure turbopumps. New designs, materials and fabrication techniques have undergone sufficient exploratory development to proceed with advanced component development and demonstration.

The reliability requirements and operational effectiveness needs of expendable propulsion systems become even more difficult to achieve in reusable systems where higher performance levels and long-life are added constraints. This task is an effort to develop turbopump and preburner technologies for cryogenic propulsion systems that meet the requirements of reusable launch system concepts. The technology developed will, however, apply to the reliability, operability, and responsiveness needs of expendable systems.

VII. SCHEDULES & MAJOR MILESTONES

Master schedule for the project will be used to support the ASTP Master Schedule and can be found at: http://www1.msfc.nasa.gov/STD/internal/index.html.

Milestones for RLV Focused Project task

NOTE: (*) Signifies the milestone represents a Level I Program milestone

1. Nonautoclave Processing, LOX Compatible Composites, and Cryogenic Insulation for Vehicle Thermal Structural Systems

6. 4QFY00 **(*)** - Advanced composite materials and foams for cryotank structures
   Output: Database of advanced composite materials for cryotank structures and foam insulation.
   Outcome: Higher temperature robust polymeric composites for cryotank applications will reduce the vehicle system weight through weight

reductions in primary and cryotank structures and TPS requirements. Advanced foams with improved performance will contribute to vehicle weight reductions and reduced maintenance and operations.

2. Joining Technology

- TBD - Reduced weight design for a composite cryotank joint.

  Output: Structural test data on joint specimens for RLV composite cryotank and dry structure. Validation of design tools for composite joints.

  Outcome: Reduced weight and improved life cycle performance for RLV composite cryotank and dry structure joints.

3. Cryogenic Tank Panel, Subcomponent Development and Integrated Structures TPS Test

- 3QFY01 - Development and validation of thermal-structural modeling techniques that correctly simulate thermal and structural responses for an integrated cryogenic tank structure within 10 percent accuracy. Establishment of failure criteria that correctly capture the ultimate failure of the integrated test article.

  Output: Predicted performance and life cycle data on an integrated cryotank and metallic TPS panel. Data on cyclic behavior and failure modes for three different cryotank wall structure designs.

  Outcome: Reduced variability in integrated cryotank/TPS design with resultant increase in robustness and operating margin for integrated RLV cryotank and TPS structures. Establishment of future RLV design requirements based upon improved understanding of failure modes and structural response.

4. Electron-beam Curing of Composite Cryogenic Propellant Tanks

- 4QFY00**(*)** - Electron beam cured subscale tank demonstrator

  Output: Database of e-beam cured epoxy composite structures and joining for nonautoclave processed composite cryotank.

  Outcome: Reduced fabrication costs for large scale RLV composite structures. Less costly approach to field repair of composite structures.

5. National Center for Advanced Manufacturing

- 2QFY00 - Graduate the first class from the Advanced Composites course taught by NCAM.

  Output: Validation of course structure and curriculum for advanced composite studies.

  Outcome: First of many students that will be provided hands-on experience in advanced composite fabrication processes.

6. Thermal Structures and Hot Structures Technologies

- 4QFY00**(*)** - Advanced metallic TPS panel fabrication and test

  Output: Database of metallic TPS coatings and materials. Advanced TPS concept validated through ground test.

  Outcome: Metallic TPS is more robust and required significantly less maintenance than current ceramic tile and blanket TPS. Metallic TPS can also offer reduced weight, improved vehicle performance through higher temperature metallic materials and all-weather operation.

- 4QFY00**(*)** - Fabrication of CRI panel and test

  Output: Database of TPS performance-Launch pad environment and flight survey of existing state-of-the-art materials. Analytical model for optimization of flexible TPS design in a virtual environment.

  Outcome: Conformable reusable insulation are ceramic blanket panels which are larger than the Shuttle RSI tiles, less expensive to manufacture and have lower maintenance costs.

7. X-33 Ground Based IR Imaging Aeroheating Experiment

- 2QFY00 - IR Measurements on STS103 to demonstrate a noninvasive global temperature measurement capability which can measure temperature on a hypersonic vehicle during boundary layer transition on re-entry. Validate the measurement and predictive tools.

  Output: Measurements of the Shuttle Orbiter during re-entry using IR cameras. Conversion of this data to a global temperature map and comparison to prediction.

Outcome: Validated analytical tools for RLV aerothermodynamic design. Improved design robustness and reduced design cycle time.

8. PEM Fuel Cell

- 4QFY00 - Demonstration of a fuel cell based on Proton Exchange Membrane
  Output: Life cycle validation of PEM technology for Five hundred hours minimum operation on GTU.
  Outcome: Highly reliable energy unit and can use propellant-grade reactants (lower purit) propellant reactants)

9. Lightweight Composite Ramp Technology Task

- 2QFY00 **(*)** - Selection of material concepts and sources to proceed.

  Output: Multiple awards for development of cooled composite ramp concepts/materials.
  Outcome: Viable methodology to produce a ramp/nozzle capable of extreme temperatures during re-entry without the need to cool the materials. Component goal for weight is 2 lb/ft2 which is significantly lighter than current technology can produce.

10. Lightweight, Long Life Thrust Cell

- 2QFY00**(*)** - Complete fabrication of Metal Matrix Composite (MMC) & Polymer Matrix Composite (PMC) thrust cell chamber demonstration units.

  Output: 5 different demonstration units, each fabricated with different composite structural jackets surrounding a new copper alloy liner.
  Outcome: Demonstrate successful fabrication of thrust cell chambers using new material systems that offer weight savings up to 40%.

- 2QFY00 - Complete fabrication of Ceramic Matrix Composite (CMC) thrust cell chamber demonstration units.

  Output: 2 different demonstration units fabricated with CMC material systems and minimal metallic supports/interfaces.
  Outcome: Demonstrate successful fabrication of CMC thrust cell chambers using composite material systems that offer weight savings up to 40%.

- 2QFY00 - Complete cold flow and hot-fire testing of MMC & PMC thrust cell chamber demonstration units.

Output: Demonstrate thermal and structural integrity of MMC & PMC designs when exposed to pressure and temperature extremes of LOX/H2 combustion environment.

Outcome: Select "best" material system and initiate fabrication of a full size "lightweight" thrust cell chamber.

- 3QFY00 - Complete hot-fire testing of CMC thrust cell chamber demonstration units.

  Output: Demonstrate thermal and structural integrity of CMC designs when exposed to pressure and temperature extremes of LOX/H2 combustion environment.

  Outcome: Compare risks & payoffs of "best" CMC material system with "best" MMC or PMC materials. Consider potential CMC material system for further development of full size "lightweight" thrust cell.

- 4QFY00 - Complete fabrication of full size "lightweight" thrust cell chamber using selected composite material system.

  Output: Full size "lightweight" chamber that can be directly compared to current thrust cell chamber made with conventional metal materials.

  Outcome: Quantify weight savings available for thrust cells made with composite materials.

- 1QFY01 - Complete hot-fire testing of full size "lightweight" thrust cell chamber.

  Output: Demonstrate thermal and structural integrity of composite thrust cell chamber when exposed to LOX/H2 combustion environment.

  Outcome: Compare performance of "lightweight" chamber directly with performance of conventional chamber design.

- 1QFY01 - Complete fabrication of a "lightweight" linear thrust cell chamber demonstration unit using new copper alloy liner and structural composite materials.

  Output: One complete linear profile chamber available for hot-fire testing.

  Outcome: Demonstrate new materials and fabrication techniques can be successfully applied to produce a "lightweight" linear thrust cell design.

11. Cu-8 Cr-4 Nb RLV Thrust Cell Liner Powder Certification

- 2QFY00 - Thermophysical properties database

  Output: Determine the thermal conductivity and thermal expansion of Cu-8 Cr-4 Nb from liquid hydrogen (-253°C) to 900°C

Outcome: Data will be used for design and trade studies in new thrust cell combustion chamber liners. Current results indicate the 15% lower thermal expansion will result in significant increases in liner lives.

- 4QFY00 - Microstructural characterization of Cu-8 Cr-4 Nb

  Output: Quantify the microstructure of Cu-8 Cr-4 Nb in all conditions tested
  Outcome: Quantifying the microstructure will enable evaluation of microstructure-property relationships. In turn, this will enable improvements in mechanical properties through processing to obtain desirable microstructures.

12. Light-Weight Gas-Generator Combustor Assembly

- 2QFY00 - Completion of sub-scale combustion chamber design.

  Output: Complete and released design drawings, completed thermal and structural analysis of sub-scale GG CMC combustion chamber. Deliver to GRC for fabrication.
  Outcome: Provides a sub-scale CMC GG chamber design to begin fabrication and testing. Ultimate goal is to develop a lighter weight GG for RLV applications.

- 4QFY00 - Complete hot-fire test for uncooled ceramic matrix composite (CMC) combustor chamber.

  Output: Demonstrate feasibility of an uncooled CMC combustor chamber for the Light-Weight Gas Generator.
  Outcome: Demonstrated technology showing applicability to uncooled CMC combustors for turbopump pre-burners.

13. Polymer Matrix Composite Lines, Valves and Ducts

- 4QFY00 - Develop a low cost/lightweight duct to help reduce the mass of propulsion systems.

  Output: Fabricate elbow sections of eight inch diameter feedlines with integral flanges using conventional autoclave techniques, solvent assisted resin transfer molding, electron-beam cure processes and carbon fiber/thermoplastic resin tape laying and compare these various fabrication methods on a performance and cost basis.
  Outcome: Reduced weight ducts and feedlines for propulsion systems to further reduce the mass fraction of any launch vehicle, which is the foremost goal of any program.

14. High Head Unshrouded Impeller Technology

- 2QFY00 - SSME-AT fuel pump water test completed

  Output: Data obtained in testing to assess the sensitivity of the performance of a high head unshrouded impeller to tip clearance. Validation of CFD predictions.
  Outcome: Validated pump hydrodynamic analysis tools in place to increase design confidence. Experimental and analytical data to guide design of pumps to reduce weight and increase engine Isp.

- 4QFY00 - Optimized two stage unshrouded impeller testing completed

  Output: Water flow testing at MSFC for design verification and analysis validation
  Outcome: Demonstration of verified unshrouded impeller design technology to significantly reduce pump weight and increase engine thrust-to-weight ratio. Validated pump hydrodynamic analysis tools in place to increase design confidence.

- 4QFY00 - Conceptual design of two-stage fuel pump

  Output: Conceptual design of a two-stage fuel pump for the RLV design point incorporating the unshrouded impeller design
  Outcome: Application of unshrouded impeller technology to the design of a fuel pump suitable for RLV. Demonstration of suitability of unshrouded impeller technology for pump design to reduce engine weight and increase engine thrust-to-weight ratio.

- 1QFY01 - Optimized two stage unshrouded impeller hydrodynamic design and analysis completed

  Output: Unshrouded two stage pump design at RLV fuel pump design point weighing approximately 700 lbs less than the baseline three stage RLV fuel pump
  Outcome: Dramatic reduction of turbopump weight resulting in significant engine weight reduction, and, consequently, increased thrust-to-weight ratio.

15. Turbine Performance Optimization Technology Task

- 1QFY01 - Optimized preliminary design chosen

  Output: Optimized preliminary turbine aerodynamic design (sizing, speed, etc.) for the RLV fuel turbine design point having a total-to-static efficiency at least

4% higher than the baseline RLV fuel turbine. Design and analysis tools for fast and accurate preliminary turbine design.

Outcome: Preliminary turbine design for the RLV fuel turbine design point with a higher efficiency allowing lower temperatures and lower mass flow rate (and higher engine Isp). Fast, accurate turbine design optimization and analysis tools in place to allow analysis of a larger design space with reduced design cycle time.

- 2QFY00 - Optimized detailed design completed

  Output: Optimized detailed turbine aerodynamic design (blade contours, spacings, etc) using the preliminary design in Milestone 1 with a total-to-static efficiency of at least 8% higher than the baseline RLV fuel turbine. Detailed unsteady CFD analysis with parametrics completed. Design and analysis tools for fast and accurate detailed turbine design.

  Outcome: Detailed turbine design for the RLV fuel turbine design point with a higher efficiency allowing lower temperatures and lower mass flow rate (and higher engine Isp). Detailed predictions of supersonic turbine flowfields providing design knowledge currently not known to the turbine community. Fast, accurate turbine design optimization and analysis tools in place to allow detailed design optimization.

- 4QFY00 - Mechanical design of turbine test rig completed

  Output: Design of the turbine test rig to be given to a vendor for fabrication.

  Outcome: Test rig to be tested in MSFC Turbine Airflow Facility for verification of design and validation of analysis.

16. Metal Matrix Composite Components

- 1QFY01 - Ox-Rich Preburner

  Output: One assembled Ox-rich Preburner (400K thrust size)

  Outcome: The preburner will provide the drive power (5035 psi, 1170°R, 860 lbm/sec GOX) for the MMC component demonstration utilizing the RRTT as the turbopump and demonstrating a reduced weight turbopump.

- 2QFY00 - MMC Material Strength Goal

  Output: The particulate-based MMC strength goal will be met (>110 ksi ultimate tensile strength) leading to fabrication of a lightweight turbopump housing, or an alternative materials development plan that achieves the strength goal will be determined.

Outcome: Achieving the material strength goal, or providing a plan for achieving the strength goal will allow lighter weight turbopumps for future engine systems.

Propulsion – Advanced System/Cycle Demonstrations

17. 650 KLBF LO2/LH2 Engine Demonstration

- 4QFY00 **(*)-** Pressure-fed Testing of Thrust Chamber Assembly for Phase I of ULCE complete

  Output: Data on performance of the pintle injector relative to droplet size and distribution/mixing of propellants.

  Outcome: Validation of pintle performance and database for anchoring design for ultra low cost engine.

18. Integrated Powerhead Demonstration

- 4QFY00 - Complete fabrication and delivery of the IPD Oxidizer turbopump.

  Output: IPD Oxidizer turbopump delivered to SSC and ready for testing.

  Outcome: New generation of highly reliable turbomachinery for Oxidizer-Rich engine applications with enhanced life and operational characteristics.

VIII. RESOURCES

A. Funding Requirements (NOA in Millions)

FY99	FY00	FY01	FY02	FY03	TOTALS
17.1	36.1	TBD	TBD	TBD	TBD

B. Institutional Requirements (FTE *)

FY99	FY00	FY01	FY02	FY03	TOTALS
17	22	TBD	TBD	TBD	TBD

* MSFC Only

IX. CONTROLS

The RLV Focused Technology Project controls start with the Program Commitment Agreement (PCA) for the ASTP Program. The PCA is interpreted at every level to meet the NASA commitment and reflected in the technical, schedule and cost requirements imposed on each of the projects.

A. NASA Headquarters

The RLV Focused Technology Project Plan establishes the top level technical, schedule, and cost controls placed on the program. A semi-annual review of this plan will be performed to accommodate the changing nature of advanced technology projects. All revisions to the Program Plan will be coordinated with the Deputy Associate Administrator for Space Transportation Technology.

B. Marshall Space Flight Center

The ASTP Program Plan and this Project Plan outline the technical, schedule and cost commitments of the RLV Focused Technology Project.

C. Change Controls

Proposed changes to project plans shall be submitted to the ASTP Program Manager for approval. Impacts to cost, schedule, and technical performance shall be included.

D. Interface Controls

Interfaces and issues among the several STD programs are controlled by the Level II Board chaired by the STD Manager. Interfaces between the RLV Focused Technology project elements are controlled by the RLV Focused Technology Project Manager.

E. Project Plan Updates

The RLV Focused Technology Project Plan updates will occur as required to reflect project changes. Annually, the RLV Focused Technology Project Plan will be assessed by the RLV Focused Technology Project Office to determine if updates are warranted. If appropriate, updates will be incorporated and will be coordinated with the ASTP Program Manager.

X. IMPLEMENTATION APPROACH

A. Implementation Plan

The RLV Focused Technology project is a development project intent on developing technologies that reduce risk and cost associated with development of reusable launch vehicles.

B. Project summary WBS.

3.2 2nd Generation RLV Focused Investment Area

3.2.1 RLV Focused Project

- Composite Tank and Structures Technologies
- National Center for Advanced Manufacturing

3.2.1.2 Thermal Protection and Hot Structures Technologies
3.2.1.3 Infrared Imaging of X-33 in Flight
3.2.1.4 PEM Fuel Cell
3.2.1.5 Lightweight Composite Ramp
3.2.1.6 Lightweight, Long Life Thrust Cell
3.2.1.7 Cu-8 Cr-4 Nb RLV Thrust Cell Liner
3.2.1.8 Light-Weight Gas-Generator Combustor Assembly
3.2.1.9 Polymer Matrix Composite Lines, Valves and Ducts
3.2.1.10 High Head Unshrouded Impeller
3.2.1.11Turbine Performance Optimization
3.2.3.12 Low-Pressure LO2/LH2 Engine Demonstration
3.2.1.13 Integrated Powerhead Demonstration

XI. ACQUISITION SUMMARY

The RLV Focused Technology Project acquisition strategy is based on both NASA in-house and contracted activities. All of the planned individual contracts are currently anticipated to be less than $100M. All activities and tasks currently maintained within the RLV Focused Technology Project are a result of NASA Research Announcement NRA8-21 Cycle 1. Because of the experimental nature of the existing contracts, NASA Research Announcements, Purchase Orders, and Support Agreements will be utilized to the greatest extent possible.

XII. PROGRAM/PROJECT DEPENDENCIES

Work done within the RLV Focused Technology project will interface with work done in the areas of Core Propulsion Technologies and Core Airframe Technologies being managed within the ASTP Office and the RLV and Pathfinder Programs managed within the Space Transportation Directorate of MSFC.

XIII. AGREEMENTS

A. Internal NASA Agreements

MSFC has been assigned as the Lead Center for the RLV Focused Technology Project and is responsible for project implementation and management. The RLV Focused Technology Project will require significant coordination between MSFC and the other participating centers. Coordination on specific technology development activities will be dictated by circumstances on an "as-needed" basis.

B. External Agreements

The RLV Focused Technology Project is expected to have external agreements through Contractors and other agencies. All external agreements will be determined by competition as part of the overall acquisition strategy.

NASA and the Air Force have signed a memorandum of agreement calling for cooperative technology development and demonstration in support of NASA’s ASTP and the military Space Operations Vehicle.

XIV. PERFORMANCE ASSURANCE

Quality

RLV Focused Technology flight hardware designed, developed and built in-house at MSFC will be in accordance with the MPG 144.1. In-house hardware may be built to dated drawings with the approval of the Lead Systems Engineer, as specified in the RLV Focused Technology Configuration Control Plan. As built drawings will be submitted to the MSFC Configuration Control Process as specified in the RLV Focused Technology Configuration Control Plan.

Due to the limited scope of the RLV Focused Technology flight demonstration experiments, flight hardware may be commercial off-the-shelf as long as it meets the requirements specified in the RLV Focused Technology Systems Specification.

RLV Focused Technology flight hardware purchased from outside vendors is not required to be ISO 9000 compliant. RLV Focused Technology flight hardware purchased from outside vendors will be based on the specific requirements of NHB 5300.4(1C). Tailoring of these requirements will be reflected in the RLV Focused Technology Quality Plan and/or in the vendor purchase order/contract.

RLV Focused Technology flight hardware purchased from outside vendors must be delivered with a Certificate of Compliance (COC) and an acceptance data package as specified in the purchase order or contract.

XV. RISK MANAGEMENT

Due to the technology development nature of the project, a Risk Management Plan will only be required for hardware developed for flight applications. This plan, if required, will document a continuous process that:

- identifies risks
- analyzes their impact and prioritizes them
- develops and carries out plans for risk mitigation, acceptance, or other action
- tracks risks and the implementation of mitigation plans
- supports informed, timely, and effective decisions to control risks and mitigation plans
- assures that risk information is communicated among all levels of the project

Risk management begins in the formulation phase with an initial risk identification and development of a Risk Management Plan and continues throughout the product's life cycle through the disposition and tracking of existing and new risks.

XVI. ENVIRONMENTAL IMPACT

Environmental impact assessment(s) shall be developed as needed by the appropriate center(s) Environmental Engineering and Management Office(s).

XVII. SAFETY

The RLV Focused Technology Project will develop safety guidelines to provide for the early identification, analysis, reduction, and/or elimination of hazards that might cause the following:

- Loss of life or injury/illness to personnel
- Damage to or loss of equipment or property (including software)
- Unexpected or collateral damage as a result of tests
- Failure of mission
- Loss of system availability
- Damage to the environment

The RLV Focused Technology Project will develop a safety plan that details such activities as system safety, reliability engineering, electronic and mechanical parts reliability, quality assurance for both hardware and software, surveillance of the development processes, “closed loop” problem failure reporting and resolution, environmental design and test requirements. The plan shall be developed early in the project formulation process for each task, as required. Mission success criteria shall be defined to aid in early assessment of the impact of risk management trade-off decisions. The safety and mission success activity shall accomplish the following:

- Provide for formal assessment and documentation of each hazard, with risks identified, analyzed, planned, tracked, and controlled.
- Provide for a safety assessment and certification regarding readiness for flight or operations, explicitly noting any exceptions arising from safety issues and concerns.
- Utilize a quality management system governed by the ISO 9000 standard, appropriate surveillance, and NASA Engineering and Quality Audit (NEQA) techniques.

XVIII. TECHNOLOGY ASSESSMENT

Ongoing assessment of needs for technology will be conducted by project management to insure that long term goals can be met.

XIX. COMMERCIALIZATION

Many of the technologies to be demonstrated have direct commercial application.

XX. REVIEWS

A. Management Reviews

Management reviews will be scheduled during the life of the project. The type and frequency of the reviews will be established according to the project unique needs and requirements. Reviews will be scheduled to keep center, program and project management informed of the current status of existing or potential problem areas. Agency management will be informed, in advance, of the schedule and agenda of the major reviews and will be invited to participate at their discretion. Special reviews by any level of management will be scheduled when the need arises.

1. Lead Center Program Management Council (PMC) Review

The Marshall Space Flight Center lead center PMC will review the RLV Focused Technology Project annually. The reviews will cover overall status information, including schedule, change, performance, funding, interfaces coordination, and other management and technical topics. The Lead Center PMC review will also assess project progress against metrics and criteria proposed in procurement instruments.

2. Quarterly Program Review

A quarterly program review will be held to review cost, schedule, and technical issues. The location of the review will be determined on a case-by-case basis. Participants will include, as a minimum, the program managers of the ASTP and STD offices.

3. Other Reviews

Other independent reviews will be scheduled as required.

B. Technical Reviews

Each technology development effort will be reviewed at six-month increments to assess progress. Decisions for continuation, redirection, and/or cancellation will be made at that time.

XXI. TAILORING

The requirements of NASA Policy Directive (NPD) 7120.4A and NASA Procedures and Guidelines (NPG) 7120.5A apply to this program as tailored by the ASTP Program Plan.

XXII. RECORDS RETENTION

The RLV Focused Technology Project Manager will determine which project records will be retained and for how long in order to ensure a permanent record of the project and lessons learned are available to benefit future NASA projects.

XXIII. CHANGE LOG

EFF. DATE	STATUS	DOC. REVISION	DESCRIPTION
Dec 13, 1999	Baseline	-	Initial issue

APPENDICES - DETAILS OF EXPERIMENTS

Appendix 1 Nonautoclave Processing, LOX Compatible Composites, and Cryogenic Insulation for Vehicle Thermal Structural Systems

Sizes of cryogenic tanks for current SSTO designs, carrying 25 000 lbs payload to low earth orbit, exceed 50 ft in length and 20 ft in width. Autoclaves large enough to cure composite structures of this size do not currently exist. Any near term decision to build an RLV of this class using composite cryogenic tanks will therefore be highly dependent upon our understanding of nonautoclave processes for fabrication and joining of large scale composite parts.

Through this task, an updated database of nonautoclave processes and their respective composites will be developed. This task will pursue two approaches for the development of nonautoclave processable composite materials and process technologies for RLV. One approach will explore the development of materials and fabrication processes for electron-beam curable polymeric composites. The other approach will examine derivatives of materials and processes developed under NASA Aeronautics Programs, including NASP, High Speed Research Program, and Advanced Composites Technology Program. Techniques which have shown promise in these programs, including advanced tow placement (ATP) , resin transfer molding and resin film infusion (RTM/RFI), will be further explored for development of materials systems for RLV. This work will be performed at the NASA Langley and Glen Research Centers, the Marshall Space Flight Center (MSFC), Oak Ridge National Laboratory (ORNL), Lockheed Martin Skunk Works (LMSW), Northrop Grumman, Applied Polymeric Composites, Rensselaer Polytechnic Institute, Science Research Labs (SRL), Boeing, and the Airforce Research Laboratory.

In addition to nonautoclave processing of composite materials, LO_X compatible resin systems, and improved cryogenic insulation, will be worked under this task.

Technical Approach

Four technical teams will address key aspects of low cost fabrication of electron-beam curable PMCs: 1) New materials formulation will be addressed by Northrop Grumman, Applied Polymeric Composites (under a Phase I SBIR), Rensselaer Polytechnic Institute, NASA Glen Research Center, and the ORNL; 2) Screening of new materials will be the focus at Langley and SRL (under a Phase I SBIR); 3) Automated Placement will addressed by SRL, and ;4) Fiber /resin interface development will be worked cooperatively by Langley, MSFC, SRL, Boeing, LMSW, AFRL, and ORNL.

Langley and Glen Research Centers and Lockheed Martin will study and develop new materials for resin transfer molding. Cryogenic foam materials will be developed by Langley and tested at Langley and Marshall.

Materials Screening and Optimization: Resin systems which use e-beam and thermal curing and can be processed by Advanced Tow Placement (ATP), or Resin Transfer Molding and Resin Film Infusion (RTM/RFI) will be screened and a comparison made based on mechanical behavior and structural stability at elevated temperatures, LO_X and LH_2 compatibility, processing method, cost, and ease of manufacture. Candidate materials for nonautoclave processes will then be selected. Concurrently, ORNL will characterize electron beam cured cationic epoxy based laminates already being developed and begin characterization of laminates made using LaRC nonautoclave thermal cure resins that are rendered electron beam curable by ORNL. The properties of the LaRC resins will be evaluated against a baseline of properties for thermally cured epoxy systems. Following characterization of the laminates, ORNL will select the best candidate for a composite cryotank and in concert with Lockheed Martin Skunk Works (LMSW) will develop an optimum process to meet the materials design requirements for the LMSW composite cryotank demonstrator.

LO_X Compatible Materials Development: New or existing polyimide matrix composites developed for the HSR Program will be fabricated, tested, and subsequently modified to enhance their LO_X compatibility. Concurrently, composites from new polyimides will be made which can meet the LO_X compatibility and airframe mechanical property requirements. Resins will be selected through a comprehensive screening process that emphasizes composite LO_X resistance and mechanical properties at the coupon level. Fabrication of these candidates will be effected by state-of-the-art processes. The candidate composites will then be tested at larger scales. A database of LO_X compatible composites will result.

Cryogenic Foam Insulation Development: Current cryogenic insulations have a limited high temperature margin, are brittle, and prone to cracks that can result in cryopumping of air. This task will develop new polyimide foams which can be used as structural or insulative material. Initial work on polyimide foams has been funded by the X-33 program and results are very promising. The LaRC developed foams will be selected by a Design of Experiment (DOE) which emphasizes cost, density, mechanical properties, thermal properties, LO_X compatibility, and flame resistance. Based on the results from the DOE, a candidate will be selected for scale-up. A database of cryogenic insulation will result .

Test Plan

Small-scale coupon tests of e-beam curable, high temperature PMCs, LO_X compatible materials and cryogenic insulating foam specimens will be conducted at Langley. Oak Ridge National Laboratory will perform testing on electron-beam curable polymer matrix composites and selected electron beam cured epoxy for LMSW cryogenic tank demonstrator. SRL will test and screen e-beam curable materials. Following a selection process, larger proof-of-scale tests will occur at Langley under the Cryotank Panel and Sub-component Task, Lockheed Martin, and Marshall Space Flight Center depending on the test required and the number and size of the specimens.

Success Criteria and Metrics

Milestone: At least one new and/or modified nonautoclave processable resin, LO_X compatible composite, and cryogenic insulation characterized for performance, cost of manufacture, and maintainability.

Output: Performance, cost, and maintainability data for an RLV: 1) nonautoclave processable resin; 2) LOX compatible resin, and; 3) cryogenic insulation. A comparison of this data to baseline performance criteria as established through system studies and data on materials currently in use for RLV composite cryotank and dry structure.

Outcome: Data on composite materials and cryogenic insulation which will enable the design of composite RLV airframe structure to be optimized with respect to cost and performance.

Resource Requirements

	FY98	FY99	FY00	TOTAL
Civil Service Workforce (FTE)	1.6	3.8	4.8	9.2
LaRC	1.5	3.5	3.5	8.5
LeRC	0.1	0.3	0.3	0.7
Support Contractor Workforce (FTE)	0.0	1.35	1.0	2.35
Civil Service Labor Costs(LaRC)($K)	70.0	158.0	158.0	386.0
Support Contractor Labor Costs($K)	0.0	135.0	100.0	235.0
Other costs	23.0	601.0	581.0	1205.0
LeRC	23.0	171.0	143.0	337.0
LaRC	0.0	430.0	438.0	868.0
TOTAL ($K)	93.0	894.0	839.0	1826.0
ONRL Task	0.0	177.0	147.0	324.0

Appendix 2 Joining Technology

This task will develop design and analysis tools and a series of innovative joint design concepts for both cryogenic tanks and dry structure. Effective joint designs will enable development of large cryogenic tanks and dry structure that can be fabricated in existing autoclave facilities. Joint designs are needed to significantly reduce structural weight and fabrication costs and greatly increase fatigue resistance and structural reliability. For large structures, efficient and reliable joint designs could significantly reduce fabrication costs by eliminating the need for an autoclave. Bolted joint designs are mature, but result in a significant weight penalty and are difficult to seal against leakage of LH_2. Bonded joint designs are less mature than bolted joint designs, but are weight efficient and are not as difficult to seal as bolted joints. However, the reliability of bonded joints in cryogenic tanks must be demonstrated. Fiber-optic sensors and health monitoring technology are needed for structural joints to provide a global health monitoring system for the vehicle structure.

Technical Approach

Innovative designs will be generated for joining sections of both cryogenic tank and dry structure. Bonded and bolted joining concepts for Y-joints (attachment of dome and shroud to tank wall), barrel joints (circumferential joints between two tank sections), and longitudinal splice joints in cryogenic tanks will be generated. Bolted joint concepts will be generated that could be used to assemble large sections of dry structure or join dry structure to cryogenic tanks. Design and analysis tools developed as a part of the NASA Aeronautics High Speed Research Program will be used in evaluating and developing the joint designs.

Each design concept will be analyzed and screening tests conducted to determine the most promising designs. The criteria used to evaluate the designs will include structural integrity, joint efficiency, fabricability, reliability and difficulty to scale up to large sizes. Results from the screening tests will be used to refine the joint designs.

A detailed thermal and structural analysis will be conducted for each joint design and the results compared with the test results. The test results will be used to validate the analytical procedures and to develop improvements to the joint designs.

A limited number of joint designs will be scaled up to large (up to 5-ft wide) panels to further verify the concept. Fiber-optic sensors will be developed and used throughout the test program to verify their performance in monitoring the structural health of joints.

Success Criteria and Metrics

Milestone: Reduced weight design for a composite cryotank joint.

Output: Structural test data on joint specimens for RLV composite cryotank and dry structure. Validation of design tools for composite joints.

Outcome: Reduced weight and improved life cycle performance for RLV composite cryotank and dry structure joints.

Resource Requirements

	FY98	FY99	FY00	TOTAL
Civil Service Workforce (FTE)	0.4	3.9	3.9	8.2
Support Contractor Workforce (FTE)	0.0	0.0	0.0	0.0
Civil Service Labor Costs($K)	19.0	176.0	176.0	371.0
Support Contractor Labor Costs($K)	0.0	0.0	0.0	0.0
Other costs	52.0	674.0	320.0	1046.0
TOTAL ($K)	71.0	850.0	496.0	1417.0

Appendix 3 Cryogenic Tank Panel, Subcomponent Development and Integrated Structure TPS Test

The lack of sufficient understanding of the thermal-structural interactions of the RLV thermal protection system with the cryogenic tank that supports it is a significant risk because of the critical need to ensure the TPS will protect the PMC structure. RLV cryogenic tanks are the largest component of vehicle dry weight and are the majority of the primary structure. Thus, to minimize vehicle dry weight and cost and assure the performance of the integrated cryotank TPS system, validation of our capability to design an integrated system and predict the performance and failure modes of the integrated system in a controlled test environment is required. Ground tests at subcomponent and component scales are the most cost-effective method of obtaining this data.–There have been few integrated tests of high speed vehicles from the cryogenic tank interior to the hot TPS. NASP task D is one of the most significant recent tests that was undertaken, but the structural-TPS concepts were much different from those proposed for RLV, which has a PMC tank and a hot--load-sharing metallic shell. Proper attachment and sealing of a multipanel TPS system on a structure undergoing mechanical and thermal distortions is a critical question that remains to be answered.

This task investigates cryogenic tank structural configurations (membrane, semi-conformal, and conformal tanks), wall constructions (variations of sandwich and stiffened, lined and unlined), cryogenic insulation concepts, and TPS support structure and attachment concepts on a consistent basis to determine the weight, integration, and operational characteristics. Existing concepts are modified and new concepts are defined, analytical studies are performed, and the most attractive concepts are determined based on analyses and tests. Full-scale subcomponents of selected concepts are fabricated and thermal-mechanically tested to validate the designs. Current fabrication processes at MSFC and at LaRC are used in a collaborative effort to manufacture advanced integrated tank test specimens for demonstration and testing. These specimens will be tested at LaRC under static and cyclic vehicle operational conditions to verify the thermal and structural characteristics, and fabrication technology utilized in the integrated concepts.

This task will demonstrate the integrated operation of full-scale cryogenic tank subcomponents and TPS under the mechanical and thermal loads expected during RLV operation. Full or partial TPS arrays, fabricated under the Metallic TPS Concepts task, will be installed on tank hardware using integration concepts developed in the latter task and fabricated in the present task. The component and subcomponents will be tested dynamically to compare with theoretical predictions and results from the subcomponent tests.

Full-scale subcomponents will be tested at LN_2 and LHe temperatures in the LaRC Cryogenic Pressure Box facility. Quartz-lamp heater arrays will be used for heating the TPS during the simulations. NDE methods will be used to evaluate effects of full and partial TPS attachment. Previously installed cryogenic tank IVHM systems and conventional instrumentation will be monitored, as well as additional IVHM and conventional instrumentation to monitor the thermal and structural performance of the TPS. The test sequence will culminate with static tests to ultimate loading conditions to determine the static strength and failure modes of the subcomponents and components.

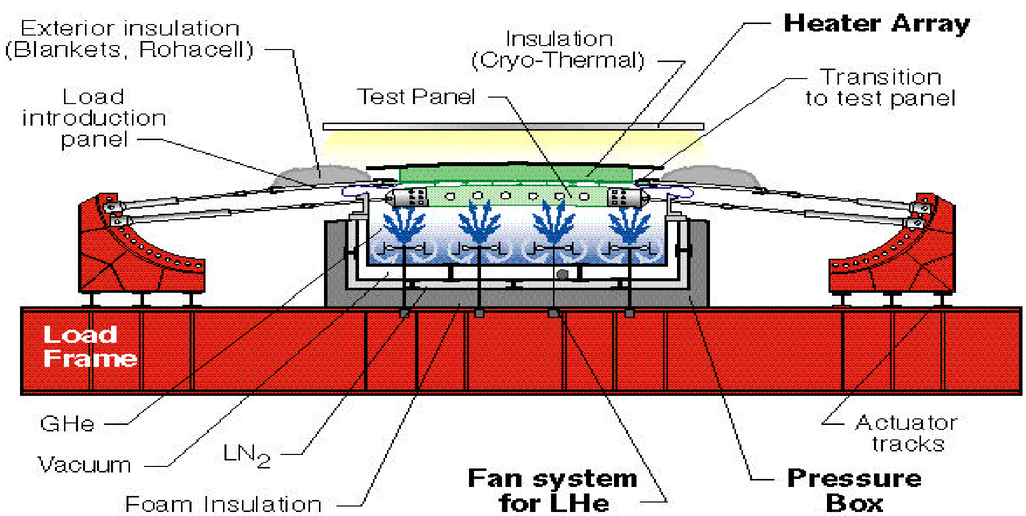
Cryogenic tank designs. Cryogenic tank structural configurations (membrane, semi-conformal, and conformal tanks), wall constructions (variations of sandwich and stiffened, lined and unlined), and cryogenic insulation concepts will be defined in this subtask. The problems of attachment methods, thermal expansion, and aero-thermal loads for TPS and cryogenic insulation will be addressed from the beginning in an integrated cryogenic tank design where the TPS (Task 6), IVHM (Task 4), and cold structure disciplines work collaboratively to reduce weight, fabrication cost, and operational costs.

Integral PMC cryogenic tank systems. Advanced, integrated PMC cryogenic tank systems defined in Subtask 1 with cryogenic insulation and TPS are thermally and structurally analyzed with the vehicle thrust and intertank structures. Thermal trade studies will size the thickness of the cryogenic insulation and TPS insulation. A 2-D sizing code being developed from an existing 1-D code developed at LaRC will size thermal insulation around the circumference of the vehicle. The structural trade study will determine the buckling strength, load carrying capability, and maximum deflections for each concept and perform preliminary optimization to determine structural weights. The impact of basic design changes will be directly related to the overall vehicle. This portion of the subtask will augment current X-33 RLV trade studies on TPS integration and cryogenic tank geometry at LaRC.

Tank concept selection and analyses. Two of the most promising concepts will be selected for further analyses and testing based on the prior work in this subtask and the smaller-scale testing in the subsequent subtask. Optimization and thermal-structural analyses using finite element codes will be performed to support detailed design optimization studies, and detailed analyses of the RLV cryogenic tank and the subcomponent cryogenic tank specimens. Correlation of test results with analysis results will be performed to increase understanding of the failure modes and to improve analysis predictions, using both commercial analysis codes and research codes having higher order shell elements for better prediction of transverse shear and out-of-plane normal stress distributions.

Structural panels. Leading integrated cryogenic tank concepts selected in the trade studies will be designed, fabricated, and tested in a building block series of tests at vehicle operational static and cyclic conditions. Specialized, elevated temperature and cryogenic mechanical testing facilities have recently been developed and are available for these tests (See figure 1.5-1 Cryogenic Pressure Box Test Facility.)

Initial demonstration tests are 1-ft by 2-ft tension/flexure, followed by 2-ft width compression tests, and finally full-scale subcomponent tests. Four subcomponent tests are planned, two 5-ft wide axial compression tests will be conducted at room temperature or at elevated temperatures using the most attractive concepts from the 2-ft width tests and the trade studies, and two Cryogenic Pressure Box tests are planned. To reduce costs, one of the Cryogenic Pressure Box tests will be of a phase I X-33, 5-ft by 6-ft LH_2 tank panel from Boeing/Rockwell. The Boeing/Rockwell IM7-977-2 graphite-epoxy panel has cobonded internal longitudinal stiffeners and mechanically fastened internal ring frames.



Two panels for a competing concept will also be fabricated and one will be tested in the Cryogenic Pressure Box facility. The Cryogenic Pressure Box tests will be cyclic, thermal-mechanical, pressurized, biaxial panel tests where cryogenic insulation and IVHM techniques would also be validated.

New Materials Subcomponents. Cryogenic foam insulations and LO_X and GO_X compatible specimens developed in Task 1 - Nonautoclave Processing, LO_X Compatible Composites, Cryogenic Insulation Development, and Cryogenic Sealants for Vehicle Thermal Structural Systems and Task 2 - Joining Technology, as well as this task, will be tested. The insulations will be tested for resistance to high temperatures (+500 F), ability to be thermally formed to shape or foamed in-place, crack resistance, and durability. The LO_X and GO_X compatible specimens will be tested for permeability and ability to seal at vehicle operational conditions to determine suitability as a tank liner.

Technical Approach

Subtask 1: Design, Fabrication, and Assembly of TPS Attachment Structure

Based on conceptual designs defined by LaRC, the design contractor will perform detailed designs of the TPS attachment structures and seals for the subcomponent and component tests. The designs will incorporate features utilized by both the aeroshell support systems and direct cryogenic tank attachment systems that are defined in Task 6. Detailed analysis of the integrated design will be performed by LaRC and analysis results for critical design conditions will be utilized by the design contractor to verify failure conditions. The attachment fabrication contractor will build the attachment hardware from the detailed designs and verify the proper fit of the attachment structure to the subcomponents and component.

The fabrication contractor will assemble the TPS attachment structures onto subcomponents and the component that have been mated to mechanical load fixtures and installed in the test systems. The installation of additional IVHM and conventional instrumentation will be accomplished by LaRC personnel or their support contractors. The fabrication contractor will then install and verify the proper installation of the TPS for the thermal-structural tests.

Subtask 2: Test Plan (including NDE and IVHM System Evaluation)

Pretest modal surveys of the integrated cryogenic tank system will be conducted for correlation with analytical models. The data will be used to verify system dynamics predictions involving complex dynamic interactions between primary structure and TPS systems. Distributed fiber-optic sensors will globally measure strain and temperature of the cryogenic tank. TPS and tank insulation performance will be determined from this data. Structural assessment of full and partial TPS attachment will be made with noncontacting optical shearographic NDE techniques. Posttest modal surveys are considered unlikely due to the application of ultimate loads, which may result in probable failure of the integrated test article.

After the modal surveys, arrays of quartz lamps will be installed adjacent to the TPS panels to supply heating. The subcomponents and components will undergo a sequence of static thermal-mechanical test conditions either simulating conditions to be encountered along critical flight conditions on an RLV, or design conditions at the corners of the vehicle operational envelope. The severity of the conditions will increase to limit and beyond to determine the ultimate static load carrying capability and failure modes. The actual combination of load conditions will be determined based on an analysis of the predicted environment and a NASA and Industry assessment of the most realistic critical flight condition.

After completion of the subcomponent tests, the conventional and IVHM sensor readings will be correlated to the analysis of the test conditions. Data fusion of IVHM and NDE measurements will be made for detection of component damage. Additional correlation will be made using the damage tolerance limits database generated in Subtask 5 of Task 4 - Damage Tolerance Design Allowables Generation. Discrepancies in the correlation will be cross-checked against the pre- and post-test inspections of the component. Additional tests of elements extracted from the integrated test hardware may be used to verify limits and adequacy of the fabrication processes.

Success Criteria and Metrics

Design and verification of at least one integrated cryogenic tank concept validated through subcomponent and component tests are the success criteria.

Milestone: Development and validation of thermal-structural modeling techniques that correctly simulate thermal and structural responses for an integrated cryogenic tank structure within 10 percent accuracy. Establishment of failure criteria that correctly capture the ultimate failure of the integrated test article.

Output: Predicted performance and life cycle data on an integrated cryotank and metallic TPS panel. Data on cyclic behavior and failure modes for three different cryotank wall structure designs.

Outcome: Reduced variability in integrated cryotank/TPS design with resultant increase in robustness and operating margin for integrated RLV cryotank and TPS structures. Establishment of future RLV design requirements based upon improved understanding of failure modes and structural response.

Resource Requirements

	FY98	FY99	FY00	FY01	TOTAL
Civil Service Workforce (LaRC) (FTE)	1.0	10.6	8.0	5.0	24.6
Support Contractor Workforce (FTE)	1.0	2.3	2.0	2.0	7.3
Civil Service Labor Costs($K)	56.0	477.0	360.0	250.0	1143.0
Support Contractor Labor Costs($K)	100.0	230.0	200.0	200.0	730.0
Other costs:	87.0	445.0	777.0	1309.0	
LaRC	32.0	412.0	732.0	300.0	1476.0
MSFC	55.0	33.0	45.0	0.0	133.0
TOTAL ($K)	243.0	1152.0	1337.0	750.0	3482.0

Appendix 4 Demonstration of Electron-beam Curable Y-joint and Cryogenic Propellant Tank With Inverted Dome

Critical processes required to validate the ability to produce large-scale composite tanks still lack the maturity to produce cryotankage of the scale and reliability required for RLV applications. Out–of-autoclave methods carry the potential of being able to produce these components without the vast expendetures required for an autoclave of the required size and capability. This task is to develop and demonstrate the technology for out-of-autoclave fabrication of a composite cryotank using electron-beam curing

To best validate the capabilities to develop and demonstrate the technology for fabricating a cryotank through E-beam curing the test article will be designed with inverted domes and unique joints to better explore the limitations of the technology.

A key goal will be to determine the structural strength at cryogenic conditions of a spliced woven Y-joint for the dual cylinder E-beam test tank. The Y-joints are located along the intersection between the dual cylinders of the E-beam test tank and have also been referred to as the double cylinder tank barrel-to-barrel joints.

Objectives:

Develop and demonstrate the technology for out-of-autoclave fabrication of a composite cryotank using electron-beam curing

Develop and demonstrate the technology for fabricating a cryotank with inverted domes and unique joints

Determine the structural strength at cryogenic conditions of a spliced woven Y-joint for the dual cylinder E-beam test tank. The Y-joints are located along the intersection between the dual cylinders of the E-beam test tank and have also been referred to as the double cylinder tank barrel-to-barrel joints. See the attached schematics of typical Y-joints.

Approach:

LMSW

- Select material system and fabrication process
- Develop limited material properties for electron-beam cured materials
- Develop and verify barrel-to-inverted dome joint design and fabrication technology for electron-beam curing

- Design and fabricate 3 foot diameter dual-lobe cylindrical cryotank with inverted domes and assemble using electron-beam cured joints

MSFC

- Verify integrity of cryotank component through hydrogen pressure tests at MSFC

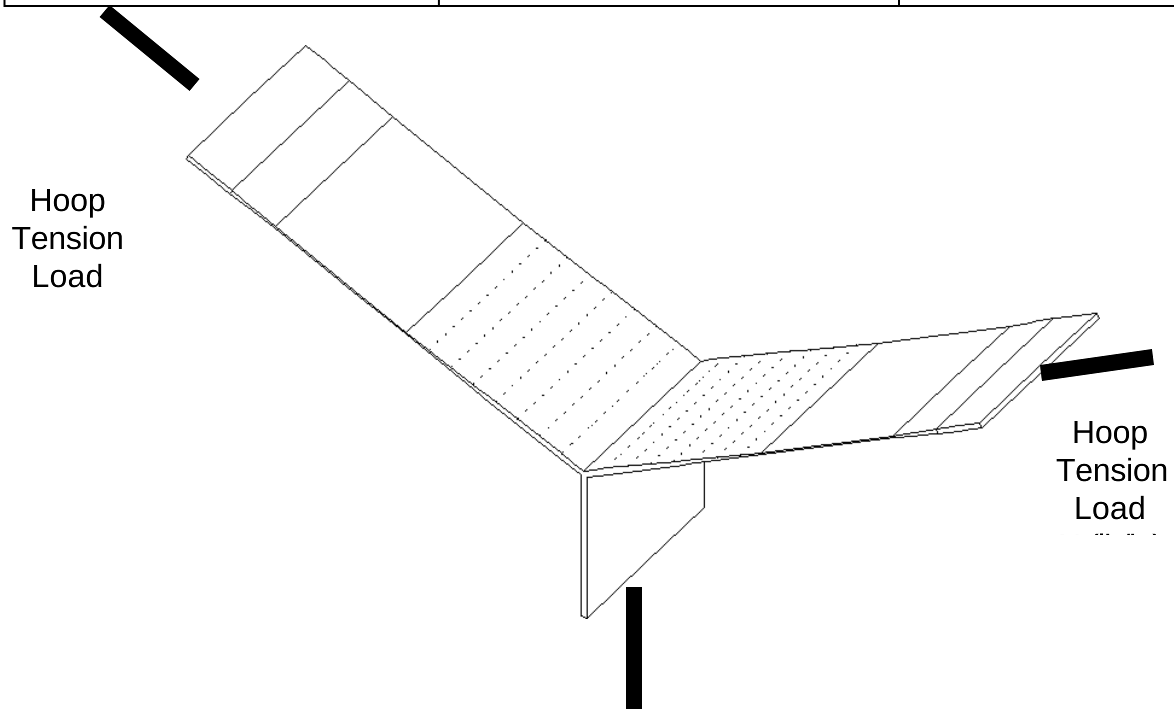
LaRC

- Test Five IM7/RS-E3 woven composite Y-joint specimens to be supplied by the LMSW. Testing will include thermal cycling, load cycling and loading of the joints to failure. Thermal cycling will consist of a 10 minute hold at each temperature extreme (-423F or +250F). The joints will then be cycled 100 times at -423F from 0% to 100% of design limit load. The joints will be pulled to failure at -423F. The double cylinder tank barrel-to-barrel joints will be loaded to 3900 lb/in ult. in the hoop direction and 1950 lb/in ult. in the axial direction.

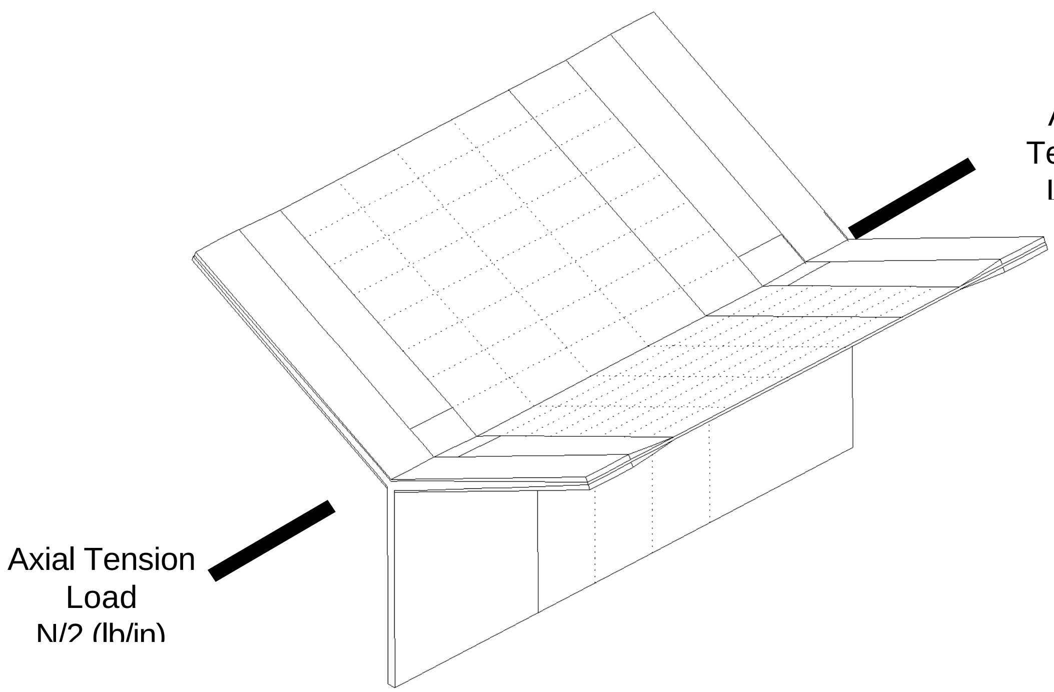
- Install instrumentation and provide test information, including procedure documentation, results documentation, and observations of failure mode, failure load, and failure progression.

- Prepare a report that includes test description, load-deflection or stress-strain curves, failure modes, test anomalies, specimen anomalies, and any other comments or observations valuable to the test.

- Design and fabricate the Y-joint test fixtures to include the mechanical load introduction fixtures and the cryogenic insulation box.



HOOP TENSION JOINT



AXIAL TENSION JOINT

Schematic of Y-Joint

FY00 Schedule Milestones

1.0 Design, fabrication, and delivery to MSFC of dual-lobe cryotank, 4Q FY00, LMSW

2.0 Design verification/testing at MSFC, 2Q FY01.

3.0 Complete Y-joint design and fabrication, 1Q FY00, LMSW.

4.0 Cryotest fixtures design and fabrication complete, 2Q FY00 LaRC

5.0 Y-joint specimen testing complete, 4Q FY00, LaRC

FY01 Schedule Milestones

- Delivery of e-beam cured tank to MSFC (1Q FY01)
- Instrument tank (1Q FY01) MSFC
- Perform pressurization tests (2Q FY01) MSFC
- Test to failure with LN2 (3Q FY01) MSFC
- Analyze failed structure and details of materials following cyclic testing (4Q FY01) MSFC, LaRC, LMSW

Estimate of Major Activities	FY 2000 O N D J F M A M J J A S
▪ Design and Fab dual-lobe cylindrical cryotank	--------------------------------
▪ Design verification/testing at MSFC	FY01
▪ Y-joints design and fabrication	--------
▪ Testing of Y-joints	--------------------------

Success Criteria and Metrics

Design and verification of a subscale composite cryogenic tank fabricated using electron beam curing. Design and validation of cryogenic tank electron beam cured y-joint concepts.

Milestone: Verification of LH2 containment and robust design and performance for an electron beam cured composite cryogenic tank subjected to realistic pressure loads for an RLV. Performance validation of an inverted dome cryogenic tank design. Establishment of failure criteria that correctly capture the ultimate failure of the electron beam cured composite cryogenic tank design.

Output: Drain and fill data for LH2 in an electron beam cured composite cryotank. Pressure loads and data on structural failure under pressure loading for cryogenic tank inverted dome design.

Outcome: Reduced variability in composite cryogenic tank design, reduced RLV weight for nested tanks using inverted dome design, and reduced cost of manufacture for composite cryogenic tanks.

Resource Requirements

	FY98	FY99	FY00	FY01	TOTAL
Civil Service Workforce (FTE)	0.4	0.4	2.0	1.2	4.0
Support Contractor Labor (FTE)	0.0	0.0	0.5	0.5	1.0
Civil Service Labor Costs($K)	18.0	18.0	100.0	60.0	96.0
Support Contractor Labor Costs($K)	0.0	0.0	50.0	50.0	100.0
Other costs	0.0	200.0	392.0	600.0	1168.0
LaRC	0.0	176.0	342.0	100.0	618.0
MSFC	0.0	0.0	50.0	500.0	550.0
TOTAL ($K)	18.0	194.0	542.0	710.0	1464.0
Lockheed Martin Contract	0.0	1000.0	1193.2	0.0	2193.2

Appendix 5 National Center for Advanced Manufacturing

The National Aeronautics and Space Administration (NASA) has established the National Center for Advanced Manufacturing (NCAM) to be performed under direction of the Office of the Chief Technologist and through the Marshall Space Flight Center (MSFQ. The NCAM has been created to address the research and technology development needs for manufacturing the next generation of reusable space transportation systems while also building a future manufacturing technology base for NASA and industry. The mission of the NCAM is to establish partnerships involving NASA, government agencies, states, universities and industry, that will develop manufacturing technologies enabling new launch vehicle and propulsion systems with orders of magnitude improvements in safety, cost and reliability.

Conceptual designs for reusable space transportation systems, including the Lockheed Martin VentureStar require unprecedented very large composite structures to achieve the necessary mass fraction for a single stage to orbit vehicle. The ability to effectively reduce system costs and development cycle times will rely on breakthroughs in the engineering environment. Furthermore, new education and training in the operations of technologically advanced manufacturing systems is critical to revolutionary product development. Current research has identified that the advanced manufacturing processes, and the level of performance of engineering tools are not available today for production of these very complex structures.

Intense global competition in the launch vehicle and aircraft businesses are requiring changes in the way U. S. aerospace industry operates to become globally competitive. In less than ten years, the U. S. has gone from dominating the launch vehicle market to owning less than 40%. NASA's interest and sponsorship of the NCAM is in direct support of helping the U. S. compete internationally.

Involving education is critical to the success of this endeavor. Development of revolutionary engineering tools will require expanding the scope of current educational achievement. The NCAM will support universities in exploratory development and participatory efforts in emerging educational technologies to provide knowledge and skills for the next generation technological workforce.

Program Objectives

- Enable manufacturing to meet NASA requirements for future space transportation
- Strengthen the competitiveness of the U.S. in aerospace and other commercial markets through advanced manufacturing
- Effect a cultural change in the manufacturing industry to an intelligent-collaborative environment
- Involve the educational community to enhance educational development and increase the number of high value jobs in the U.S.

Approach

Provide a world-class manufacturing center for the U.S. Aerospace Industry NASA committed to utilize the infrastructure of the Michoud Assembly Facility (MAF) located in New Orleans, LA for large scale manufacturing development. Expand NASA/MSFC's unique experience and relationships within the aerospace community to include state governments and universities
June, 1998, Governor of Louisiana pledges support to fund large composite manufacturing capability contingent on NASA/Lockheed Martin VentureStaro
March 29, 1999, Memorandum of Understanding signed by NASA, the State of Louisiana, and the University of New Orleans (UNO)
Maintain government role in technology development for the support of industry
Direct critical investments in cross-cutting, fundamental technologies

Institutionalize the intelligent synthesis environment and virtual partnership concepts within manufacturing community
Leverage resources of involved parties June, 1999, $4 M appropriated by the Louisiana Legislature for state-of-the-art automated fiber placement equipment for MAF
Facilitate hands-on and virtual training at MSFC facilities and remote sites, and participate in university curricula and course development
August, 1999, UNO starts graduate level courses in composites engineering in temporary facilities at MAF
October, 1999, Louisiana Department of Labor commits to provide funds as part of their incumbent worker training program

Resource Requirements:

	FY99	FY00	FY01	FY02	FY03	FY04	FY05
Total $M							
ARC							
GRC							
MSFC		4	5.4	5.4	6	6	6
LaRC							
Civil Servant,FTEs							
ARC							
GRC							
LaRC							
MSFC		2	2.5	2.5	3	3	3

Appendix 6 Thermal Protection and Hot Structures Technologies

Areas critical to the development of lightweight robust thermal protection systems for RLV are addressed in this technology element: 1) Metallic Thermal Protection Systems (TPS); 2) Advanced Durable Blanket Technology, and; 3) Integrated Hot Structure. The large maintenance burden of the Reusable Surface Insulation (RSI) ceramic tile TPS for the Shuttle (estimated between 40 000 and 70 000 hr/flight) is one of the principle reasons for seeking alternative approaches for acreage TPS on RLV. Metallic TPS is baselined in the X-33 RLV program. Metallic thermal protection systems (TPS) have the potential to be more robust and to require significantly less maintenance than current ceramic tile and blanket TPS. With improved structural integration, materials, insulation, and attachments, metallic TPS can also offer reduced weight, improved vehicle performance through higher TPS temperatures, and all-weather operation. Another approach, aimed at reducing vehicle life cycle costs, is conformable reusable insulation (CRI). These are ceramic blanket panels which are larger than the RSI tiles, less expensive to manufacture, and have lower maintenance unit costs.

The thermal limits of metallic and CRI TPS restrict the application of these TPS. Areas of the vehicle, such as leading edges and control surfaces, which experience higher thermal loads require a different approach, such as hot structures, to reduce overall vehicle weight and maintenance. Hot structures offer the potential to significantly reduce the TPS requirement for an RLV and thereby reduce vehicle weight and maintenance. However, to date, many of the hot structures have been costly to manufacture and the material system characteristics do not support high load bearing structures. In this activity, Northrop Grumman will explore the development of a structurally integrated high temperature wing design for an RLV. The wing structure will integrate a polymer matrix composite (PMC) primary structure with a strain-compliant Ceramic Matrix Composite (CMC) Hot Structure through co-processing and explore the use of 3D textiles woven preform technology with resin film infusion to reduce manufacturing cost.

Three tasks are included in this technology element:
Metallic TPS Design, Constituents and Fabrication Techniques
Advanced Durable Blanket Technololgy
High Temperature Integrated Structures

Subtask 1 - Metallic TPS Design, Constituents and Fabrication Techniques

Under this task improved metallic TPS concepts will be developed which build on the strengths of previous NASA LaRC concepts and the X-33 metallic TPS concepts. The improved concepts will be designed to offer lower risk, subsurface panel-to-panel seals, cooler subsurface attachments, adaptability to a variety of substructure configurations, and potentially higher temperature operation while remaining mass competitive with current concepts. This task is set up to deliver tested advanced metallic TPS components in time to support critical RLV decisions. Honeycomb coupon tests will demonstrate the performance of the selected outer surface material, fabrication technique and coating under rain erosion, and low speed impact conditions. Two-panel arrays will be fabricated and tested to demonstrate static thermal performance under RLV entry conditions and structural integrity under launch acoustic loads. A 2-ft-square array will be fabricated and tested to demonstrate thermal performance under hot gas flow conditions.

TPS Concept Development, Design, and Fabrication

Current cooperative tasks with Lockheed Martin Skunk Works and B. F. Goodrich will serve as starting points for this subtask. Design requirements and characteristic thermal and mechanical loads will be developed using input from these potential customers as well as ongoing LaRC system studies. These requirements will be used in design and trade studies to identify promising concepts. Materials and coatings development support will be provided by the Metallic Materials Branch at LaRC (Task 5 - Constituents and Fabrication Techniques for Metallic TPS) and fabrication vendors. The work will also include the development of NDE and IVHM for TPS to reduce maintenance and inspection requirements. Specimen tests of design and fabrication features along with analytical results will be used for concept selection. Fabrication approaches and cost estimates will be solicited from several vendors. A single vendor will be selected to perform detailed designs and fabrication of selected concepts. TPS panels will be fabricated for thermal vacuum, acoustic and arc jet testing. Panel variations may include several different attachment concepts and insulation packages.

Integration of TPS and Vehicle Structure; Attachment System and Sealing

Reliable, lightweight integration of the TPS with the vehicle structure will be critical for a successful RLV. Attaching TPS to cryogenic tanks or an aeroshell pose significant design challenges. The design work will address metallic TPS attachment and sealing for different structural configurations. Designs will be developed which ease panel installation and removal and minimize cost, weight, and impact on thermal performance. Attachment concepts will be incorporated into the 2-panel arrays. Tests of integrated cryogenic tank and TPS are proposed in Task 7 - Integrated PMC Cryogenic Tank and TPS Structure.

Insulation Characterization and Optimization

Metallic TPS concepts separate the insulation materials from any structural functions. This separation allows for the use of the lightest, most efficient insulation available. An effort is currently in progress at LaRC to measure the conductivity of fibrous and multilayer insulations over a range of temperatures and pressures and to develop analytical models to describe their behavior. These experimental and analytical results will be used to tailor an insulation package for typical RLV environments. Insulation packages will be incorporated into the 2-panel array for evaluation.

Constiuents and Fabrication Processes

Achieving improved metallic TPS will require fabrication of mass-efficient, foil-gage sandwich structures from advanced materials that offer lower mass, higher operating temperatures and/or lower fabrication cost. Materials to be considered will include advanced titanium alloys (Ti-1100, Ti-6242), titanium aluminides (orthorhombic, gamma), and iron and nickel based superalloys (PM1000, PM2000). Advanced joining techniques such as welding, brazing, weld-brazing, and enhanced diffusion bonding must be developed for these materials.

Surface properties of candidate materials including oxidation resistance, emissivity, and catalycity will be determined. Durable, lightweight coatings will be developed to improve the surface properties where needed. Materials, processing, and coatings will be assessed for application to honeycomb core sandwich TPS structure and these improved processes will be used in Task 6 - Metallic TPS Concepts.

Thin-gage, lightweight alloys will reduce the TPS weight and hence the total vehicle weight. Thermal control coatings and lightweight, high-temperature alloys will improve the TPS and structural temperature capability resulting in improved thermal and structural efficiency and enhanced vehicle mission performance. Advanced joining techniques and processing routes will improve performance and reduce manufacturing time and cost. TPS part count will be reduced, thus reducing the system complexity and hence reducing the vehicle assembly time, labor, and cost.

Experience with materials and metallic honeycomb core sandwich development for hot structure during the National Aero-Space Plane (NASP) and the generic hypersonics programs, as well as on the current X-33 TPS and High Speed Civil Transport (HSCT) programs will be leveraged for this task. Identification of TPS requirements and task selection decisions regarding materials, coatings, and processes will be done in concert with the primary customers for this product and with personnel in the LaRC Thermal Structures Branch, Structures Division.

Materials and Fabrication Techniques Defined

First, TPS requirements will be identified and candidate design concepts, materials, and fabrication processes will be selected. A baseline TPS system will be identified and used as a benchmark for the measurement and evaluation of progress and success based on performance in simulated service environments and system weight. The effect of the fabrication processes on the mechanical properties and microstructure of the constituent materials will be determined, and the processes will be optimized to maximize performance of the constituent materials and joint efficiency.

Second, subelement specimens will be fabricated and tested to evaluate the mechanical properties of the fabricated TPS panels, as well as the effect of simulated service conditions on the panel performance. Mechanical properties of materials and TPS subelements will be measured from -200 F to +1800 F.

Testing

Design requirements and characteristic thermal and mechanical loads will be used in design and trade studies to identify the most promising TPS concepts. Designs will include potential attachment and seal schemes as well as insulation packages. Thermal conductivity of selected insulation packages will be measured over a range of temperatures and pressures. Selected alloys will be exposed to processing environments (brazing, diffusion bonding, coating) to determine the effects of processing on mechanical properties. The effects of the most promising environmental and thermal control coatings on the mechanical performance of selected alloys will be determined. Tensile coupon (coated and un-coated) will be subjected to simulated reentry environments in the multi-parameter simulator and tested for mechanical and optical property degradation which will be correlated with alloy/coating microstructure and interactions. Coated alloys will be tested in the HYMETS to determine durability in dynamic air-flow. Alloys and coatings will be selected for application to full-scale TPS panels. Thermal and structural properties of sub-scale, coated TPS panels will be determined and will be used in conjunction with the analytical studies to select particular concepts to be fabricated in full-scale.

Schedule - major activities	FY 2000 O N D J F M A M J J A S
• Tailored insulation development	------------------------------------
• TPS concept development & design	---------------------------------------
• Coating development, fabrication & testing	--
• Alloy/coating/joints testing & analysis	--
• Full scale TPS fabrication	---------------------

Complete thermal-pressure testing on selected insulation packages. (2Q FY00)
Select TPS concepts, including seals and attachments for full-scale fabrication. (2Q FY00)

Complete detailed thermal and mechanical models including transient thermal analysis, insulation optimization, and static, flutter,sonic fatigue, and creep/lowcycle fatigue analysis (3Q FY00)
Validate alloy/coating system performance in simulated entry environments, (Hymets and multi-parameter simulator) including residual property determination. (3Q FY00)
Establish contract for full-size TPS panel design and fabrication. (3Q FY00)
Complete effects of joining processes on alloy & sandwich panel performance. (4Q FY00)
Establish scale-up coating processes for coatings of choice. (1ft x 1ft panels) (4Q FY00)

Success Criteria and Metrics

An advanced TPS panel will be compared to baseline panel performance and to nonmetallic TPS (tiles, blankets) in terms of weight, thermal characteristics, environmental compatibility, structural performance, and cost. TPS performance, weight, and functionality will be measured against X-33 and prior metallic TPS, as well as tile and blanket concepts.
Milestone: A 5% weight per unit area reduction in RLV metallic TPS.
Output: Demonstrate a metallic thermal protection system design with a 5% reduction in weight per unit area over the X-33 metallic TPS design with the same thermal structural performance.
Outcome: Lighter weight, more weather capable thermal protection system for reusable launch vehicles.

Resource Requirements

	FY98	FY99	FY00	TOTAL
Civil Service Workforce (FTE)	2.0	6.8	5.5	14.3
Support Contractor Workforce (FTE)	0.0	2.4	2.2	4.6
Civil Service Labor Costs($K)	91.0	307.0	275.0	673.0
Support Contractor Labor Costs($K)	0.0	315.0	275.0	590.0
Other costs:				
LaRC	0.0	359.0	214.0	573.0
TOTAL ($K)				

Subtask 2 - Advanced Durable Blanket TPS

The post-flight inspection and refurbishment of Thermal Protection Systems is a significant operations cost and vehicle turn-around time driver for Reusable Launch Vehicle (RLV) systems. One major contributor to this impact is the use of a large number of Reusable Surface Insulation (RSI) tiles, the small size of which is driven by the material properties of the tile. For example, on the Space Shuttle, there are on the order of 20,000 RSI tiles. This large number, with the associated tile dimensional requirements, coatings, gap fillers, inspection, repair, installation, rewaterproofing, and the paperwork to track these changes on a tile by tile basis. The use of conformable reusable insulation (CRI) offers the opportunity for replacing a large number of RSI tiles with a fewer number of blanket panels or sections for acreage TPS coverage. The reduced number of TPS units, along with the lower fabrication and maintenance unit costs for CRI, can yield lower vehicle life-cycle costs.

However, current flexibel blanket insulation have characteristics which limit their use, principally being lwer thermal limits compared to tiles, higher flexibility, which can change the boundary layer, and therefore the thermal loading of the TPS and lower durability.

This task will develop an advanced family of CRI materials and design options. Of paticular interest is the application of these CRI designs to windward vehicle surfaces. Another major focus of this task is to conduct a thorough set of tests to characterize the performance of both existing TPS and candidate CRI designs, and to distribute a uniform characterization data set to the TPS design and operations community.

The Space Technology Division (Code AS) of the Ames Research Center is the manager of this task and has responsibility for defining and maintaining the overall task plan. Participants in this task include the Ames Research Center, the Boeing Corporation, and the Langley Research Center. Task products, contract deliverables, interim project milestones, and the schedule for technical interchange meetings are defined in the task plan. Current copies of the task plan are provided to the Langley RLV FAST project manager, and the MSFC RLV Focused Project Manager.

Technical Approach

Current state-of-the-art Flexible Blanket TPS will provide the basis for evolution and development resulting in a family of CRI material systems. These will be tailored to meet the demands of vehicle environments that have previously precluded the use of blanket insulations. The various activities comprising this project have been organized into the following tasks to facilitate technology development and project management.

Windward Surface CRI Design

Aerodynamic and thermal loads for a conceptual RLV will be compared with measured performance limits of existing Flexible Blanket TPS to identify the nature and extent of improvements required for windward surface applications. Analytical modeling will be used to predict the performance impact of various proposed improvements to avoid pursuit of less worthy concepts.

CRI OML Surface Development

Based on the results from the aerodynamic and thermal loads analysis, the architecture of the OML surface fabric, and the nature of the surface coating material, will be modified to meet the projected performance requirements. Aeroacoustic testing of thermally conditioned samples will be used for screening of various fabric design and coating concepts. Further testing, including arc jet and rain impact testing, will be performed on the most promising concepts to provide the basis for further downselect.

The selected CRI concepts will be evaluated to determine their waterproofing and rewaterproofing requirements. Processing commensurate with vehicle operational goals will be developed and demonstrated on a 50 square foot panel array.

Options for attachment of the CRI to a vehicle will be examined based on the configuration and materials of each concept. Mechanical testing will assess the sufficiency of each attachment/CRI combination.

CRI Evaluation/Characterization Testing

Characterization of the CRI concepts will include assessment of:

Thermal conductivity
Specific Heat
Emissivity at elevated temperature
Radiant heating response
Aeroacoustic durability
Vibroacoustic durability

Boeing facilities will be used for bulk producibility demonstration of each CRI concept.

CRI Aerothermal Validation

Two cycles of arc jet and wind tunnel facilities will be utilized to subject CRI concepts to aerothermal and aerodynamic forces that are representative of worst-case values anticipated for the windward side of the target RLV concept vehicle.

Planning activities and concept design for additional operatinal verification provided by flight testing on one or more vehicle (F-15, pathfinder hypersonic vehicle, Shuttle) will also be performed.

TPS Weatherizatikon Evaluation

The launch pad weather resistance of existing TPS, including rigid tiles, flexible blankets, and metallic systems, will be investigated using Boeing's Launch Pad Rain/Wind facility. Performance of CRI systems will also be assessed in this manner as they become available.

Major Deliverables

Database of TPS performance – Launch Pad Environment & Flight
Survey of existing SOA materials (including advanced CRI concepts). Commonality of
Test article and facility allows direct comparison of TPS types.
Analytical model for optimization of flexible TPS design in a virtual environment.
Advanced CRI materials suitable for windward side use on RLVs (resulting in drammaticaly decreased TPS fabrication & maintenance costs.

Roles and Responsibilities

<u>Ames Research Center (ARC)</u> – responsible for the overall task management and contract administration. Reviews and approves contract deliverables. ARC provides fabricated DurAFRSI blankets for testing, is conducting arc jet and wind tunnel testing, is defining blanket characterization tests and data reporting formats, is reviewing and evaluating all characterization test data, and is providing consulting services to Boeing on CRI design and testing options. Approximately 4-6 multiple panel DurAFRSI blanket test articles will be fabricated to conduct all required characterization tests. ARC will provide task plans and status to the Langley RLV FAST project manager and the MSFC Advanced Space Transportation Program Office at MSFC.

Langley Research Center (LaRC)- responsible for providing to Boeing an assessment of current metallic TPS technology and existing TPS products for evaluation and inclusion in a database. LaRC will provide consultation to Boeing on design and testing options, including test fixture and attachment methods.

Boeing – is responsible for the bulk of the activities for this task, which are focused on CRI design, development , and fabrication, as well as characterization testing of the CRI designs. The scope of the Boeing activities is defined in NASA Cooperative Agreement NCC2-9015.

Boeing will conduct team telecons as required to review task status and to dientify significant issues. Boeing will also provide monthly status reports to the ARC task manager and will provide contract deliverables per the cooperative agreement.

Resource Requirements

Organization	FY98	FY99	FY00	Total
ARC				
CS FTE				
CS $K				
Other Costs				
Total	120	174.5	205	**499.5**
LaRC				
CS FTE	0.0	0.0	0.6	
CS $K	0	0	27	
Other Costs	0	0	108	
Total	0	0	135	**135**
Boeing				
$K	217	688.5	460	**1365.5**
TOTAL TASK	337	863	800	**2000**

Subtask 3 - High Temperature Integrated Structures

The objective of this task is to develop and demonstrate a mass- efficient, integrated hot structure for application to an RLV wing. Additional objectives for the design of this integrated hot structure include reduced RLV development and operations costs by incorporating the thermal protection function into the integrated load bearing structure. The more rob ust outer surface will reduce maintenance and improve operability.

Technical Approach

The approach is to develop an integrated hot structures where a polymer matrix composite (PMC) is co-cured to a ceramic matrix composite (CMC) structure. The first step is to fabricate a PMC with a high temperature PETI RFI resin and verify the ability to co-cure it with a CMC facesheet. Carbon foam thermal properties will be determined at NASA LaRC. The carbon foam will be cast in place between CMC facesheets. The CMC/foam sandwich panel will be co-cured with a PMC structure. NG will fabricate all test articles and will perform all ambient temperature testing except for the integrated hot structure. LaRC will perform all elevated temperature testing.

The challenges are the strain incompatibility of the PMC and CMC structures and the resulting loads on the integrated structure, the thermal performance of the integrated structure, and the manufacturing of this advanced integrated hot structure. Joining the structure will be an issue as well, but is beyond the scope of this activity.

Objectives:

Develop a light weight integrated polymer matrix composite (PMC)/ceramic matrix composite (CMC) structure for use as dry structure on an RLV. This will be accomplished by:

- Fabricating and testing coupons for evaluation of mechanical properties at ambient and elevated temperature
- Fabricating and testing sub elements for evaluation of mechanical properties at ambient and elevated temperature
- Fabricating and testing a single sub-scale integrated hot structure (PMC/CMC) at realistic temperatures(FY01)

FY00 Schedule and Major Activities:

	O N D J F M A M J J A S
Northrup Grumman	
• Fabricate coupons	----------------------------------
• Fabricate sub-elements	------------------------
• Fabricate integrated hot structure	-----------
LaRC	
• Test coupons	---------------
• Test sub-elements	-----------

FY00 Planned Schedule and Milestones:
Northrup Grumman
1. Fabricate coupons (3Q, FY00)
2. Fabricate sub-elements (4Q, FY00)

LaRC
1. Test coupons (4Q, FY00)
2. Test subelements (4Q, FY00)

FY01 Planned Schedule and Milestones

Fabricate the integrated hot structure wing segment (2Q FY01) Northrop-Grumman
Deliver integrated hot sgtructure wing segment to LaRC (2Q FY01)
Test integrated hot structure wing segment (4QFY01) LaRC

Success Criteria and Metrics
Milestone: A 30% weight reduction when compared to an insulated wing design for a winged body Singe Stage To Orbit (SSTO) RLV.
Output: Thermal structural design, fabrication and structural test data on an integrated hot structure wing segment which has been designed to the loads and specifications for an winged body design of SSTO RLV.
Outcome: Lighter weight, more robust wing structures for reusable launch vehicles.

Resource Requirements

	FY98	FY99	FY00	TOTAL
Civil Service Workforce (FTE)	0.2	4.1	1.0	5.1
Support Contractor Workforce (FTE)	0.0	0.1	0.1	0.2
Civil Service Labor Costs($K)	9.0	185.0	45.0	239.0
Support Contractor Labor Costs($K)	0.0	10.0	10.0	20.0
Funds Provided Directly to				
Northrop Grumman	0.0	1689	800.0	2489.0
Other costs:				
LaRC	0.0	162	40.0	202.0
TOTAL ($K)	9.0	2046	895.0	2950.0

Appendix 7 Infrared Imaging of X-33 in Flight

The validation of experimental and computational predictive techniques is essential for the success of single-stage-to-orbit technology and future space transportation technology development. Conservatism in design must be eliminated or minimized to enable low cost space transportation. Outer mold lines (OML) must provide the aerodynamic performance to meet mission objectives with the minimum surface area (translates to weight) possible. The aerodynamic and aeroheating disciplines are the drivers for vehicle design and provide critical inputs to other disciplines such as control system design, materials, and structures. Aerodynamic and aeroheating data provide the input for thermal protection system (TPS) material selection and sizing, which must represent the minimum weight to ensure survivability and reusability. For autonomous landing vehicles, the aerodynamic performance and margins must be known precisely throughout the entire flight trajectory. To achieve these goals of optimum design of future RLV's, reduced vehicle design cycle time, and to enhance U.S. space launch competitiveness, designers must have highly accurate, calibrated and validated tools for prediction of aerodynamic performance and aeroheating characteristics. Aerothermodynamic flight data provides the ultimate means for tool validation. Once validated, these tools may be used with confidence for the next generation of RLV's and vehicles such as military spaceplanes, and Shuttle Orbiters.

Technical Approach

Aeroheating information will be measured during flights of the Shuttle Orbiter and X-33 via ground-based infrared emission cameras as the X-33 descends through the atmosphere. The primary emphasis of this task will be to obtain global surface temperature distributions in flight over a range of hypersonic conditions including the regions of peak heating and expected boundary layer transition during reentry. This will be accomplished nonintrusively (no impact on the vehicle airframe nor on operations) via the BMDO/ISTEF. This task requires the reconstruction of the as flown trajectory and atmosphere from the flight data. In addition, the surface temperature-time measurements currently planned will be required to establish quantitative levels. The position, velocity, and orientation vectors and encountered atmosphere state properties data provide the inputs to generate the necessary scaling conditions needed in the analysis of the thermal data. The priority is to identify, monitor, and quantify hypersonic boundary layer transition (provide benchmark laminar and fully turbulent aeroheating data) for validation of prediction techniques; and map transition movement to calibrate and validate boundary layer transition prediction techniques.

FY00 Schedule and Major Activities:

	O	N	D	J	F	M	A	M	J	J	A	S
• IR Measurements on STS103	---											
• Data Analysis/Temp. Maps			----------------------------									

- Test Plan for X-33 ----------------------------

Success Criteria and Metrics

Milestone: Demonstrate a noninvasive global temperature measurement capability which can measure temperature on a hypersonic vehicle during boundary layer transition on re-entry. Validate the measurement and predictive tools.

Output: Measurements of the Shuttle Orbiter during re-entry using IR cameras. Conversion of this data to a global temperature map and comparison to prediction.

Outcome: Validated analytical tools for RLV aerothermodynamic design. Improved design robustness and reduced design cycle time.

Resource Requirements

	FY98	FY99	FY00	FY01	TOTAL
Civil Service Workforce (FTE)	0.0	1.5	1.6	1.6	4.7
Support Contractor Workforce (FTE)	0.0	1.0	0.5	0.5	2.0
Civil Service Labor Costs($K)	0.0	68.0	73.0	80.0	220.0
Support Contractor Labor Costs($K)	0.0	100.0	50.0	50.0	200.0
Other costs:	13.0	192.0	507.0	300.0	1012.0
LaRC	13.0	92.0	107.0	100.0	312.0
BMDO		0.0	100.0	400.0	200.0
700.0					
TOTAL ($K)	13.0	360.0	630.0	430.0	1433.0

Appendix 8 Proton Exchange Membrane PEM Fuel Cell

The Proton Exchange Membrane (PEM) Fuel Cell task is managed by the NASA Glen Research Center. This task is a 26-month program to develop PEM fuel cell technology for potential RLV applications. Compared to the present alkaline fuel cell technology (used on the Shuttle), the PEM technology offers the following advantages:

Lower cost with significant future cost reductions
Lower maintenance and longer life (10,000 hours v.s. 2000 hours)
More fuel efficient (approximately 10% less fuel for same power level)
Reduced weight (approximately 50% more power for same weight)
Can use less pure propellant-grade reactants

Technical Approach

The design and development process will consist of three design iterations, two sub-module stack iterations will be followed by the final full-stack iteration. Each iteration includes design, fabrication, and test of fuel cell hardware. Life testing results of a ground test unit (GTU) based on Allied Signal's automotive design will be utilized in the design process. The GTUwill be fabricated and put on life test early in the task.

The following is the Work Breakdown Structure (WBS) for this task:
RLV Requirements Definition
Ground Test Unit (GTU) Fabrication and Test
Electrode Development
Bipolar Plate Development
RLV PEM Development
RLV Full-size Stack Fabrication and Test
Program management

Success Criteria

The goal of this task is to achieve 2000 hours minimum operation on GTU to demonstrate compatibility with pure oxygen reactant and to demonstrate performance goals of 5.25kW, 30V on full stack test article.

Roles and responsibilities

Glen Research Center (GRC) – is responsible for overall task manangement, provides fuel cell requirements to Allied Signal, performs life testing of two stack test articles and reviews test results. GRC is responsible for providing a task plan to LaRC RLV FAST project manager and the RLV Focused Project manager at MSFC and for providing monthly status reports.

Marshall Space Flight Center (MSFC) - provides fuel cell requirements input and reviews test results.

Schedule

PDR for sub-module stack #1	Sep. 1998
Delivery of GTU to NASA GRC for life testing	Dec. 1998
CDR for Sub-module stack #1	Dec. 1998
Fabrication of sub-module stack #1 complete	Mar. 1999
Testing of sub-module stack #1 complete	Apr. 1999
CDR for sub-module stack #2	Jun. 1999
Fabrication of sub-module stack #2 complete	Sep. 1999
Testing of sub-module stack #2 complete	Nov. 1999
CDR for full size fuel cell stack	Dec. 1999
Fabrication of full size stack complete	Apr. 2000
Life test of GTU complete	Apr. 2000
Performance test of full size stack at AS complete	May 2000
Delivery of full size stack to NASA GRC for life test	Jun. 2000
Life test of full size stack complete	Aug. 2000
Final report complete	Sep. 2000

Resource Requirements

Resource Data for PEM Fuel Cell Task

Overall Funding by Team Member

Team Member	FY98	FY99	FY00
Allied Signal	$255,854.00	$665,349.00	$312,661.00
NASA LeRC	$31,300.00	$85,500.00	$116,500.00
NASA MSFC	$4,800.00	$1,300.00	$2,800.00
Totals	$291,954.00	$752,149.00	$431,961.00

Labor Cost Breakdown for NASA Team Members

LeRC FTE's	0.30	0.95	1.10
LeRC FTE $	$14,900	$45,500	$53,500
LeRC SSC's	0.14	0.11	0.17
LeRC SSC $	$16,400	$13,000	$20,000
MSFC FTE's	0.30	0.08	0.18
MSFC FTE $	$4,800	$1,300	$2,800

Appendix 9 Lightweight Composite Ramp Technology Task

Metallic nozzles and the required supporting hardware required to cool the inner wall of the nozzle of a traditional liquid rocket engine have accounted for a very high percentage of the propulsion system weight. This trait is common regardless of the nozzle configuration, i.e., bell or aerospike ramp. The integration of advanced ceramics into nozzle fabrication offers a unique, but extremely challenging, opportunity to reduce the weight of the nozzle significantly. This high-temperature tolerant material may also eliminate the requirement to actively cool the nozzle ramp of the Aerospike during the critical descent where currently projected heat loads are the most severe.

Objectives

The proposed task is distinctly different, but builds upon, the baseline funded RLV composite nozzle task. Currently proposed material system concepts for the aerospike cooled composite nozzle ramp base program are challenged to meet the weight goal of 2 pounds/ft^2. Due to the development schedule imposed upon the baseline cooled composite nozzle ramp task, certain advanced, innovative concepts will not be selected as they lack the maturity necessary to meet the aggressive baseline development plan delivery schedule. The technological progression and sub-scale demonstration of these concepts towards the RLV performance goals is expected to provide critical and potentially enabling input into the RLV go/no go decision - even though the program outlined here does not meet the large scale test article test demonstration requirement currently imposed by the baseline RLV program. These innovative concepts however, offer significant potential advantages in the critical areas of performance, cost, reliability and inspectability.

Deliverables

Products for the nozzle technology program will include the following:
Material concept selection
Preliminary concept design/design review (PDR)
Enabling Technology Demonstration test series results
Hydrogen containment demonstration (burst test results)
Thermal performance demonstration (Vortek tests)
CMC Panel Joining Demonstration (ARCJoint at GRC)*
Hot gas performance demonstration (GRC tests)
Mechanical properties for design and analysis
Manufacturing scale-up demonstration article
Design for Large Scale Test Article

Technical Approach

The technical approach will follow the established roadmap demonstrated for cooled composite structures under the NASP program and adapted for the baseline RLV aerospike cooled composite nozzle ramp program, with one exception. An enabling technology demonstration test series has been incorporated to focus initial development activities on those key technologies which lack maturity and are critical to the successful development of the selected concept. At the conclusion of the ETD, sufficient information will have been generated to support a go/no go decision. Results of these early demonstrations will be incorporated into the design and manufacturing processes for the burst, thermal performance, and hot gas performance test articles. The roadmap from the baseline RLV nozzle ramp (currently being finalized) which addresses these tests, and from which experience this proposed task will benefit, is provided as Reference Document 1. Lessons learned from this fabrication cycle will feed the MTD task which, combined with results of the performance tests will culminate with a Phase II design for the follow-on LSTA. Enabling thermal, mechanical, and performance requirements, manifolding, and scale-up capability will have been demonstrated.

Go/No Go Points

At the conclusion of the planned ETD test series, the team will evaluate the results of the tests and determine the direction for the next phase of the program. Three potential paths will be considered. Successful completion of the ETD test series would enable the material concept to proceed along the baseline RLV nozzle ramp development approach including the burst, Vortek, and hot gas performance testing and MTD fabrication. This is the proposed baseline path for this task. An alternative path involving additional focused technology development would be selected if the team determined that the results of the ETD test series demonstrated sufficient potential for maturation and entry into the RLV nozzle ramp baseline evaluation test series. At this point, the team would define those specific tests/developments required, and an abbreviated ETD phase two would be conducted and results evaluated prior to initiation of the burst, thermal performance, and hot gas performance testing and MTD scale-up. The final option would be termination of the task if the results of the ETD test series indicated that the possibility for successful maturation and/or full scale development was improbable.

Task Benefits

The innovative concepts proposed under this task offer significant potential advantages in the critical areas of performance, cost, reliability and inspectability. They offer a projected 25% savings in areal weight (based on current estimates) relative to the more mature concepts under consideration in the base programs. Cost reductions will be achieved through less complicated design for the cooling channels resulting in improved, simpler manufacturing processes. The same design features which enable improved producibility also increase reliability by reducing the number of critical failure modes and reduce inspection requirements. The actual benefits will be only those associated with the selected concept as all candidate concepts do not possess the same benefits or combination of benefits. The goal of the proposed task is to mature the manufacturing technologies and demonstrate concept feasibility for full scale development.

Statement of Work

This statement of work (SOW) describes the requirements for the design, analysis, fabrication, testing, and technology maturation necessary to demonstrate material system concept feasibility for full scale development for the RLV aerospike engine nozzle ramp.

Material System Selection

Based upon information provided by material suppliers in support of the baseline RLV nozzle ramp development program, there are material system concepts, and elements, which offer the potential benefits of reduced weight and cost, but which lack the maturity necessary to meet the aggressive schedule of the baseline RLV nozzle ramp program. These high risk material system candidates will be developed to meet the requirements defined in the existing flysheet specification for the RLV nozzle ramp (Rocketdyne document, RD98-101). The team, consisting of representatives from NASA Centers, MSFC, GRC, and LaRC, Rocketdyne, Rockwell Science Center, and sub-contractors (e.g. AFRL/ML, SRI, ASM), will select the most promising candidate material system. The review, evaluation, and selection process will be led by NASA/MSFC. A competitive solicitation for industry proposals will be used.

Preliminary Design and Analysis

The first task will be to refine the design of the selected material system concept. The design and analysis task will focus on those key technologies which are enabling to meet the specified design requirements and also on those technology areas which are known to be immature, and limiting to further development of the concept. Known technology challenge areas include hydrogen containment/coolant channel architecture, structural capability, attachment methodology, and manifolding. Micromechanics analysis to refine and optimize reinforcement fiber architecture is currently planned to be an integral element of this task. Design requirements will be those provided in RD98-101 used for the baseline RLV nozzle ramp program. This task will be led by NASA/MSFC with support from NASA/LaRC, Rocketdyne, and industry (subcontractor TBD). A preliminary design review will be held to conclude this task. Results of the design and analysis activities will be reviewed. Recommendations for special focus areas and test article designs for the following Enabling Technology Demonstration task will be presented and reviewed by the team.

Enabling Technology Demonstration

Those technologies associated with the selected concept as immature/enabling will be the focus of this phase of the project. During the prior task involving preliminary design and analysis of the material system concept, specific areas will have been identified that require maturation/demonstration prior to proceeding to the baseline development phase which involves burst, thermal performance, and hot gas performance testing, as well as the MTD scale-up. The material supplier will fabricate test coupons according to the designs developed during the prior phase to mature and demonstrate capabilities in these critical areas. Tests will be conducted by appropriate organizations, dependent upon the specific technology maturation areas identified.

At the conclusion of the ETD test series, the team will review the results and determine the direction for the next phase of the project. Three options have been identified for this Go/No Go decision:

1. Proceed to baseline development/ evaluation phase
2. Proceed to augmented ETD Phase 2 test series for further required technology maturation
3. Terminate the project.

If the decision is made to proceed to an augmented ETD Phase 2 approach, the team will define the tests and test articles necessary to successfully demonstrate readiness to proceed to baseline development/evaluation phase.

Material Concept Evaluation

This phase of the project will proceed following the same approach, using the same test facilities as the baseline RLV nozzle ramp project. This philosophy will enable direct one-to-one comparison of results from tests of the high risk concept to those from the baseline program. Further, as the high risk material concept will lag the baseline program, lessons learned from these tests will benefit the high risk task. There are three evaluation testing elements within this phase plus another task for generation of mechanical, thermal, and physical properties of substrate materials and/or macrostructural/thermal properties of the material system concept. Again, the approach followed for this latter task will parallel that followed for the baseline RLV nozzle ramp program, which is in the process of being finalized. The best description of the requirements for these tests can be found in the RLV Composite Nozzle Ramp Development Test Program (98-JV-008). The May 21, 1998 Draft version, representing the collective inputs of the baseline RLV nozzle ramp team, is attached. This document, in its final form, will be the baseline document for the following tasks.

1. Subscale Panels for Burst and LCF Testing

2. Subscale Panels for Radiative Testing

3. Subscale Panels for Aeroconvective Testing

4. Composite Material Properties

Pre and post test thermal and thermostructural analyses will be performed. This analysis effort will be led by MSFC with support from LaRC, Rocketdyne, and industry (subcontractor TBD). Specimens will be instrumented according to plans and procedures developed and demonstrated under the baseline RLV nozzle ramp program. Nondestructive evaluation (NDE) will be performed according to plans and procedures developed and demonstrated under the baseline RLV nozzle ramp program. It is expected that both the instrumentation and NDE plans developed by the baseline program will be applicable to the selected high risk material system concept. However, should this not be the case, the team will develop instrumentation and NDE plans appropriate for the selected material system concept.

Manufacturing Technology Demonstration (MTD)

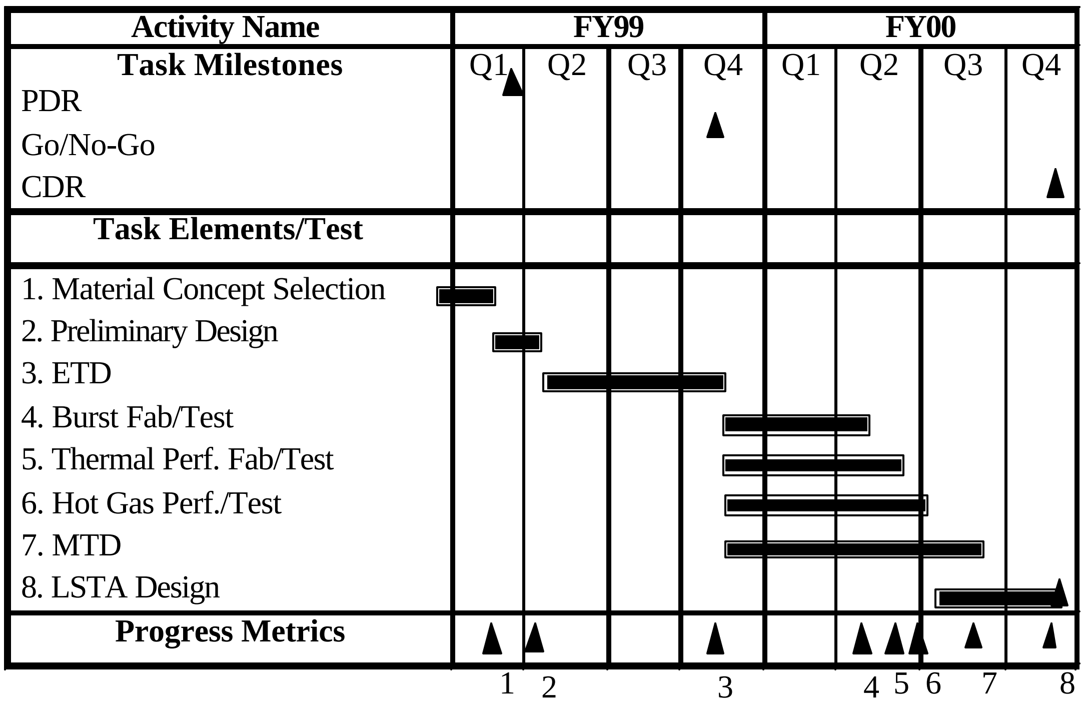
In this task, the capability to scale-up the manufacturing process from the coupon level will be demonstrated. The test article dimensions will be approximately 10" wide by 36" in the axial, or coolant channel direction with curvature in this axial direction. The MTD will be evaluated with NDE methodology, according to the baseline RLV nozzle ramp plan or using NDE methodology appropriate for the selected material system concept. Manifolding will be required. Backside attachment structures representative of that which would be proposed for the Large Scale Test Article (LSTA) will be included in panel fabrication. No testing other than quality assessment through NDE methodology will be performed on the MTD panel. Results of this scale-up trial are expected to provide significant benefit to the fabrication of the LSTA in the follow-on project.

LSTA Design

Following the completion of the material system concept evaluation testing phase and generation of the requisite mechanical, thermal, and physical properties, this information will be utilized for design of the large scale test article. The LSTA will be a curved panel of approximate dimensions of 30" in width by 60" in length containing manifolding and attachments to interface with the Three Cell Test Rig at MSFC. This design activity will be led by NASA/MSFC with support from NASA/LaRC, Rocketdyne, and industry (subcontractor TBD).

Schedule and Budget

	FY98	FY99	FY00	TOTAL
PROPOSED COSTS				
1. SALARIES AND WAGES (FTE's)				
• MSFC	2	4	4	10
• LeRC	0.1	0.4	0.4	0.9
• LaRC	0.2	1.2	2.0	3.4
2. FRINGE BENEFITS	N/A	N/A	N/A	N/A
3. TEST EQUIPMENT/FIXTURES	25	100	25	150
4. SUPPORT CONTRACTOR SERVICES (Engineers, Technicians)	-	50	100	150
5. DOMESTIC AND FOREIGN TRAVEL	4	10	10	24
6. SUBCONTRACTS	200	750	875	1825
7. LeRC COST	5	75	75	155
LaRC COST	15	85	95	195
AFML COST	-	-	70	70
BOEING/ROCKETDYNE COST	30	50	50	130
ROCKWELL SCIENCE CENTER COST	20	40	40	100
COST SHARING	**301.3**	**1165.6**	**1346.4**	**2813.3**



Metrics and Potential Off Ramps- (1) Material concept selection. (2) Preliminary design review. (3) ETD and associated Go/No-Go Decision. (4) Hydrogen containment successfully demonstrated (burst test). (5) Acceptable thermal performance. (6) Acceptable hot gas performance. (7) Successful scale up (MTD). (8) LSTA design.

Task Management

The Light weight Nozzle Ramp team is chartered to develop a lightweight Nozzle Ramp design using the projected RS-2200 Aerospike operating conditions as the design conditions for the effort. Key opportunities for weight reduction and performance enhancement are in innovative use of ceramic composite materials and advanced manufacturing techniques. This team will use all MSFC and support contractor personnel required to ensure success. As a minimum, the following disciplines will be members of the Comosite Ramp CDT:

Team Lead Structural
Manufacturing Specialist
Design Stress Analyst
Materials Test Specialist
Loads Analyst
Propulsion Test Specialist
Thermal Analyst

Material Selection Specialist

Appendix 10 Lightweight, Long Life Thrust Cell

` The overall objective of this program is to develop lightweight alternatives for thrust cells that are exposed to extreme hot gas environments. Currently, thrust cells for the Reusable Launch Vehicle (RLV) program's Venturestar and X-33 engines comprise approximately 25% of the engine weight, and their hot gas walls (HGW) are exposed to high temperature combustion products that can limit the thrust cell's life. Reducing weight while overcoming thermal issues can benefit these launch vehicle programs, as well as the engines being developed for the HEDS (Human Exploration & Development of Space) program.

This project plan outlines the tasks that will be performed to address the development of lightweight, long life alternatives to the current thrust cell designs. These tasks were defined to address material, design, and fabrication issues, and to perform appropriate analysis and testing for developing and verifying concepts. Schedule, budget, and personnel aspects for managing this program are also outlined.

Status of Current Technology

While most engine concepts currently use metal liners in their combustion chambers to handle the high heat loads produced by the combustion process, nonmetallic composite materials are now being investigated as lightweight alternatives for various engine components. Several NASA and Air Force SBIR's are currently investigating these materials for combustion devices such as nozzle ramps, chamber liners, and small thrusters. In task 7.3, GRC will be developing technology focused on using a copper-chromium-niobium alloy to reduce thrust cell liner weight. Should the decision be made that the use of a CMC liner is of too great a risk to proceed into full scale development, the Cu-Cr-Nb material will serve as an alternate for this task. This lightweight metal alloy can serve as an alternate for this task if the nonmetallic materials offer too much risk for full scale development.

Materials such as carbon fiber/silica carbide (C/SiC) and similar variations of ceramic matrix composites (CMC) offer potential weight savings of 30-40%, but many issues still need to be addressed. The correct fibers, architecture, and matrix of materials used in these composites are critical for meeting thermal and structural requirements. Also, these materials will be sensitive to oxidation or chemical reactions on the HGW, so the boundary layer of the flow has to be carefully considered to insure life requirements are met. Pressure containment by the composite wall, possible cooling tubes, or a backup structure is another issue to be addressed.

Various cooling schemes will actually be investigated in this program. To take advantage of the porosity that these materials can offer, transpiration cooling becomes an option to consider. However, if transpiration cooling proves unfeasible, film cooling requirements and the design issues for regenerative cooling must be examined. Additional fabrication and design issues include (but are not limited to) structural closeouts, manifolding, and bonding of dissimilar materials.

Technical Approach

The technical approach addresses the issues associated with using various composite materials in thrust cell liners. Work will be focused on the requirements for the X-33 and Venturestar engines to generate feasible, alternate concepts for the baseline thrust cell design.

FY98 - Design requirements defined, available technology reviewed, and possible alternate concepts identified. Contracts for material investigation and fabrication demonstrations awarded, as required. Appropriate testing and analysis will be performed to resolve issues and demonstrate technologies before selecting the most promising concept.
FY99. This concept will be matured further to actually create a full size thrust cell for hot-fire testing. If material concepts are not mature enough to fabricate a thrust cell in a timely manner, this program will recommend the additional required technologies to investigate.
FY00 - Full size fabrication and hot-fire testing.

Scope of Work - Task Breakdown

Rocketdyne Division of Boeing North American will be consulted for details of the current thrust cell baseline design for the X-33 and Venturestar engines. They will also help define the design requirements to establish weight and cycle life goals.

Based on this information, a review will be conducted of all government and private industry research on relevant nonmetallic materials. Some of this research is already being managed by NASA. Specifically, lightweight, high temperature materials and various cooling schemes are being investigated for the HEDS robotic mission's ascent engine. Composites are also being investigated for a nozzle ramp to support the X-33's aerospike design. The nozzle ramp effort has developed some possible useful material systems, such as CSiC with integrated coolant channels and CSiC with embedded refractory metal tubes as coolant channels. The Air Force is investigating similar CSiC with embedded refractory tubes in a contoured chamber profile. The progress and technology development of these programs and many others will be considered to understand the options currently available and determine the specific needs of this program's investigation.

After the requirements have been compiled and the available technology reviewed, alternate concepts will be defined to develop new designs and solutions that offer reduced weight and acceptable life.

Material Development

Appropriate materials for consideration will be developed in cooperation with GRC and specific subcontractors. Various material candidates will be defined that can potentially meet the requirements. Issues for these materials will be defined to plan the development required for each. Samples will be fabricated for appropriate testing to address both mechanical and thermal concerns.

Fabrication issues specific to material development will be defined and addressed by generating fabrication samples (e.g., How easily can the material be formed into a contoured profile? How easily can it incorporate coolant channels? What porosity can be achieved for transpiration cooling?). The cooling requirements of each material will have to be considered carefully, as well. Materials that can withstand high temperatures by relying on only film cooling or transpiration cooling may offer additional weight savings, and possibly provide simpler operation and fabrication by eliminating the larger manifolding and tubing required for regenerative cooling.

As the material technology of each alternative matures, their weight and life issues will be assessed to make sure the appropriate materials are always being investigated to meet the design requirements. The weight and life gains for the most promising materials will be compared to their technical issues, and the concept that appears to provide the highest payoff in the shortest amount of time will be pursued further. This chosen material system will be developed with the cooling/structural design and fabrication process to produce a full size thrust cell.

If it is concluded that none of the material systems are feasible to produce a full size thrust cell before the end of FY00, a program will be recommended to mature the required material technology.

Design

While the required material system is being developed, additional design issues will be addressed. Specifically, the cooling system has to be evaluated to determine how feasible transpiration cooling will be with the material candidates. If the material can provide such cooling, the structural closeout and coolant distribution need to be designed appropriately. Since these non-metallic materials are sensitive to oxidation problems, transpiration cooling with hydrogen offers an opportunity to locally reduce the amount of oxygen on the HGW. Unfortunately, achieving this benefit creates additional operational concerns with a LOX lead engine, so such a design will also have to carefully review the engine requirements. For either transpiration or regenerative cooling, the required coolant distribution system and manifold designs must be developed.

Additional design issues must consider the bonding and fabrication process requirements of the thrust cell, as well as the attachment methods used to integrate the thrust cell into the engine system.

Since this program intends to hot-fire test a full size thrust cell, an appropriate injector will be required. Rocketdyne will be consulted to make sure that appropriate injector interface issues are addressed in the design.

Analysis

Thermal and structural analysis will be required to support material development, cooling requirements, and overall design issues. Additional analyses will evaluate the thrust cell's specific operating and performance requirements.

Analysis will also be used to generate the appropriate test conditions of the full scale thrust cell to verify that performance and life requirements are achieved. Rocketdyne has already hot-fire tested X-33 thrust cell development hardware at MSFC. The baseline flight hardware is scheduled for hot-fire testing at MSFC in FY98. Therefore, hot-fire data is already available for analysis to establish the combustion environment that the thrust cell will be exposed to. Analytical and test results for this program will be compared to the available hot-fire data already obtained by MSFC and Rocketdyne.

Fabrication

New materials, as well as the chosen cooling system will obviously create new fabrication issues. Bonding dissimilar materials will have to be addressed to incorporate a nonmetallic liner into a metallic structural support. Bonding the thrust cell to the injector will also have to be considered. This program will review and take advantage of any applicable research on these bonding issues. Rocketdyne and additional subcontractors will be consulted to make fabrication samples that demonstrate the required bonding technology.

Additional fabrication issues will be defined as the design matures. When appropriate, fabrication samples will be made to address these issues. In addition, this program intends to verify all fabrication issues by creating a full size thrust cell for hot-fire testing. The full size thrust cell will be fabricated by Rocketdyne and/or appropriate subcontractors.

Testing

In addition to testing appropriate material samples (e.g., mechanical, physical, environmental, and thermal specimens), subelement fabrication samples will be tested as required. Such testing is likely to be performed to verify bond joint integrity, coolant flow distribution, pressure containment, and manifold designs. Required NDE and contamination analysis will be performed as required to further support component development. Microstructural analysis will also be conducted on the material samples and subelements.

Finally, a full size thrust cell will be hot-fire tested under relevant operating conditions to verify the complete design. An appropriate test plan and test matrix will be developed to define the specific test conditions and number of tests. Data from these tests will validate that the life and weight goals are achievable. A full size injector will be requested from Rocketdyne to support the hot-fire testing of the thrust cell.

Participants

Current facilities available to conduct the required testing include:

NASA MSFC's Transportation Directorate - It is anticipated that hot-fire testing of the full size thrust cell will be conducted in the east test area of MSFC's Transportation Directorate. This research facility is a diversified component test facility for test programs that require high pressure and/or cryogenic propellants. The facility consists of several test positions for subscale and larger, full scale testing. Signal conditioning equipment, appropriate instrumentation, and special recording equipment for high frequency data are available. Thrust capability up to 750,000 lbf is available.

This facility has previously supported hot-fire testing of several X-33 tasks, including performance and stability testing of single thrust cell development hardware in FY96. Multiple thrust cells were tested with an aerospike nozzle ramp in FY97, and single thrust cell flight hardware is scheduled for performance testing in FY98.

NASA MSFC's Engineering Directorate - MSFC's materials laboratories have the ability to conduct the following materials tests on composites samples: tensile, low cycle fatigue, high frequency fatigue, and creep to 1400 deg C in air. Room temperature interlaminar shear testing can also be performed. In addition, this laboratory operates facilities to perform extensive non-destructive tests on composite materials.

NASA Glen Research Center - NASA GRC has processing, testing and analysis facilities which have been developed to handle the unique aspects of ceramic matrix composite materials. These include hot presses, vacuum furnaces, and tensile and compressive setups unique to testing ceramic matrix composite materials, and the usual array of analytical tools present at a national research facility.

In addition, NASA GRC has multi-purpose combustion gas facilities capable of testing a variety of combustion sub-elements or components. These facilities are currently being utilized to support X-33 and other RLV tasks (e.g., single thrust cell composite nozzle ramp screening). Research can be conducted using gaseous hydrogen, gaseous oxygen, liquid oxygen and liquid hydrogen up to 2000 lbf thrust. Combustion chamber pressure up to 1000 psig are possible. The cell is fully equipped with a high speed data acquisition system and thrust measurement.

If necessary, testing will be considered at other government agencies or subcontractor facilities.

Task Management

Lightweight, Long Life Thrust Cell Component Development Team
This team is chartered to develop a lightweight thrust cell using the projected RS-2200 Aerospike operating conditions as the design conditions for the effort. Key opportunities for weight reduction and performance enhancement are an innovative use of ceramic composite materials and advanced manufacturing techniques. The team will be responsible for meeting the requirements of the test facility and providing a safe test article for the project. This team will use all MSFC and support contractor personnel required to ensure success. As a minimum, the following disciplines will be members of the Thrust Cell CDT:
Team Lead Structural
Design Stress Analyst
Loads Analyst
Thermal Analyst
Material Selection Specialist
Manufacturing Specialist
Materials Test Specialist
Propulsion Test Specialist

Participants and Responsibilities

MSFC will lead and support the entire team in all activities, including the design process, material selection, analytical assessments, and program/progress reviews. MSFC's Propulsion Laboratory (EP) will lead the program with significant support from the Materials & Processes Laboratory (EH), and the Structures and Dynamics Laboratory (ED) will provide necessary thermal, structural, and CFD analysis.

GRC will support material selection activities, testing, and program evaluation.

Rocketdyne will support the team by defining the design requirements, providing hardware integration details, resolving fabrication issues, and supporting program/progress reviews. Rocketdyne will also support hot-fire testing by providing the appropriate injector hardware to test the thrust cell.

Additional industry subcontractors will be solicited to provide design inputs, help evaluate and select material systems, and support component fabrication.

Reviews

Program/progress reviews will be conducted on a regular basis. Written monthly progress reports will be provided. A final report detailing the progress of the program will also be provided.

A preliminary design review (PDR) will be conducted after requirements have been defined, available technology has been reviewed, and materials have been investigated. A critical design review (CDR) will be conducted before fabrication of the full size thrust cell begins.

A detailed test plan and test matrix will be compiled to establish the required hot-fire test program. Prior to hot-fire testing, a test readiness review (TRR) will be conducted.

Deliverables

In addition to required material samples and fabrication demonstration components, this program will provide a full size thrust cell for hot-fire testing.

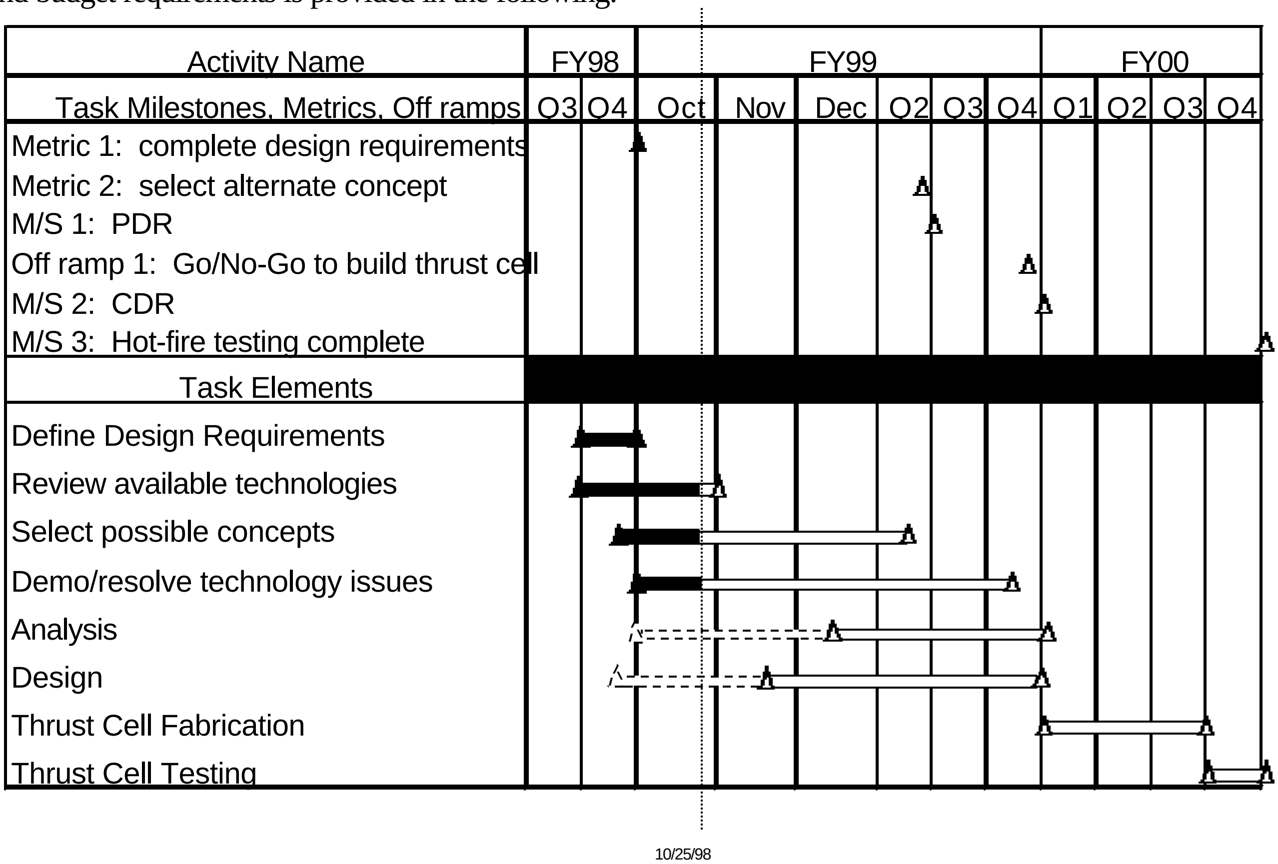
Milestones

Several milestones have been set for this program, as well as additional metrics to gauge the program's progress. Milestones include a PDR and CDR. Prior to attempting the CDR, however, a Go/No-Go decision will be made. This decision will consider the probability of successfully making a full size thrust cell by the end of FY00. If it does not appear that the material systems are mature enough to support full scale fabrication, the program will instead define the technologies still required to create a successful lightweight, long life alternate concept. If it is possible for the program to successfully fabricate a full size thrust cell, the final milestone will mark test completion - when weight and life goals have been verified.

Additional metrics include: (1) completing the definition of the design requirements, (2) selecting the most promising alternate concept after all material, design, and fabrication issues have been addressed, and (3) completing all the technology demonstrations required to insure that the selected concept will meet weight and life goals.

Schedule and Budget

A simplified schedule showing milestones and task elements along with projected manpower and budget requirements is provided in the following:



Subcontractors that will be considered for competitive procurement with this budget include:

Refractory Composites, Inc. (RCI)
Hypertherm
Atlantic Research Corporation
B.F. Goodrich
Energy Science Laboratory, Inc.
DuPont Lanxide
Ultramet

Current ROM Cost Estimates:

	FY98*	FY99	FY00	Total
MSFC FTE's	1.2	6.4	6.4	14.0
Matl. development	0	$800K	0	
RD support	0	$200K	$100K	
LeRC support	$5K	$76K	$77K	
Matl. testing	0	$100K		
Analysis	0	$100K		
Misc.	$8.6K	$348K	$50K	
Thrust Cell Fab	0	0	$300K	
Thrust Cell Testing	0	0	$1149K	
Total	$13.6K	$1624K	$1676K	$3314K

Appendix 11 Cu-8 Cr-4 Nb RLV Thrust Cell Liner Program

The Reusable Launch Vehicle (RLV) will require new materials in order to achieve its goals of decreased launch costs and increased reliability and durability. One area of particular concern is the thrust cell of the aerospike engine. Already the Rocketdyne Division of Boeing is baselining the new NASA GRC developed Cu-8 Cr-4 Nb (Cu-8 at.% Cr-4 at.% Nb) alloy for use in the RLV engine thrust cell liner. Utilization of the current Space Shuttle Main Engine (SSME) liner material, NARloy-Z (Cu-3 wt.% Ag-0.5 wt.% Zr), could severely limit the life of the engines and may not provide the necessary capabilities to achieve the payload goals of the RLV program. NARloy-Z has also demonstrated two major problems, blanching and the failure of the chamber liner wall over cooling channels known as the “dog house” failure. Conditions in the RLV thrust cell could cause similar failures.

Cu-8 Cr-4 Nb originally was developed at the NASA Glen Research Center under the Earth-To-Orbit (ETO) program as a replacement for NARloy-Z[1]. Considerable experience with the material including commercial production of large powder lots has been amassed. Rods, bars and sheet product have been made. The tensile and yield strengths of Cu-8 Cr-4 Nb between 23°C and 800°C (73°F and 1472°F) are approximately double those of NARloy-Z. The ultimate tensile strengths are also significantly higher. Ductilities are slightly lower than NARloy-Z, but still exceed 25% elongation. Creep lives of Cu-8 Cr-4 Nb are up to three orders of magnitude greater than NARloy-Z with the biggest benefits coming at higher temperatures[2]. Preliminary low cycle fatigue (LCF) testing showed that the lives of Cu-8 Cr-4 Nb were at least equal to NARloy-Z at room temperature and exceeded NARloy-Z by 50% to 150% at 538°C (1000°F) and 649°C (1200°F). The thermal conductivity of Cu-8 Cr-4 Nb is at least 72% the thermal conductivity of copper. Results from Rocketdyne[3] indicate that improved processing can increase the thermal conductivity to values approaching that of copper. Cu-8 Cr-4 Nb also offers a lower thermal expansion and 5% less density than NARloy-Z.
The Cu-8 Cr-4 Nb thrust cell liner can also be combined with the MSFC lightweight thrust cell jacket to lower the overall thrust cell system weight and improve reliability.

Potential System Payoffs

Cu-8 Cr-4 Nb is a relatively well characterized material with known properties. Comparing the properties of Cu-8 Cr-4 Nb and NARloy-Z, in general Cu-8 Cr-4 Nb has equivalent mechanical and thermophysical properties to NARloy-Z at a temperature 100°C to 150°C (180°F to 270°F) higher than NARloy-Z. This means that with a simple substitution of Cu-8 Cr-4 Nb for NARloy-Z, the operating temperature can be increased by 100°C (180°F). The liner weight would also be decreased by 5% due to Cu-8 Cr-4 Nb’s lower density. The thermally induced stresses would not be increased at these higher operating temperatures due to Cu-8 Cr-4 Nb’s lower coefficient of thermal expansion (CTE).

The overall system benefits to increasing the liner temperature will be highly dependent on the operating cycle. The benefits can be taken in a balance of increases in performance, durability and safety. One benefit to increasing the liner hot side temperature would be to reduce coolant requirements for the liner. Less coolant flow through the channels would lower the demand on the pump. The coolant pressure drop through the chamber could also be reduced. These factors would allow redesign of the fuel pump and other related hardware for reduced weight and increased reliability. Engine cycle studies will be needed to evaluate the various trade-offs.

Additional system benefits are possible by redesigning the engine to take maximum advantage of the improved material capabilities of Cu-8 Cr-4 Nb, e.g., thinning the liner wall for reduced weight. Reductions in weight of the liner by 25% or more could be achievable.

The substantial increases in strength, creep life and low cycle fatigue (LCF) life combined with higher temperature capabilities directly translate into a larger margin of safety from localized temperature spikes and other anomalies. The overall increase in properties will also translate into a more robust engine requiring less maintenance and greater mean time between failure (MTBF). Inspections and related work can also be reduced.

Scope Of Work

The work will consist of two main areas: development of a design level database for use in the RLV program and analysis of the material to better understand the microstructure-properties relationship. The understanding can be used to improve materials processing and properties as well as allow better modelling and life prediction in the future. As a consequence of the database development, the new powder supplier, Crucible Research, will be qualified as a supplier of Cu-8 Cr-4 Nb powder to the RLV program.

Powder Certification And Design Level Database Generation

The goal of the powder certification will be to generate a design level database suitable for designing and manufacturing an RLV thrust cell liner from Crucible Research powder by the end of FY 2000. The database will be transferred to Rocketdyne after it is generated for their use. It will also be provided to other RLV participants if needed.

Prior work has used Cu-8 Cr-4 Nb powder supplied by the Special Metals Corporation. Because they made a business decision to no longer supply Cu alloys, Crucible Research Corporation has become the primary supplier. While preliminary work has shown their most recent powder to be comparable to the Special Metals product, full powder certification and design level testing has not been conducted on Crucible Research powder to certify them as a vendor. Options on an existing contract have been established to purchase up to 500 pounds of powder for certification in FY 98. A breakdown of the proposed testing schedule appears in Figure 1.

Mechanical Testing

To certify Crucible Research, a statistical Design of Experiment (DOE) for the Cu-8 Cr-4 Nb powder will be generated based on five individual production runs. NASA Glen Research Center will have primary responsibility for extrusion and testing of the Crucible Research powder.

The primary mechanical properties of interest are tensile strength, creep life and low cycle fatigue life. A complete test matrix with the maximum number of tests to be conducted is given in Table 1. A full DOE and statistical analysis will be conducted by Dennis Keller of RWQS via a small purchase contract funded out of the NASA GRC money to minimize the amount of actual testing and maximize the quality of the data generated. A maximum of 60 tensile tests will be used to characterize the tensile properties of the Crucible Research material between room temperature and 800°C (1472°F). In addition, up to 30 cryogenic tensile tests will be conducted under contract to determine the low temperature material behavior of Cu-8 Cr-4 Nb. This testing will give design level results that will allow determination of average properties and statistical confidence intervals.

After consultation with Rocketdyne and others involved in designing the RLV thrust cell liner, a DOE of up to 135 creep tests using temperatures between 500°C and 800°C (932°F and 1472°F) will be conducted. Stress levels will be selected to give lives consistent with anticipated life requirements for RLV thrust cells. Vacuum creep testing will be conducted using Brew creep frames modified for computer data acquisition.

Up to 135 low cycle fatigue tests will be conducted between room temperature and 650°C (1202°F) using total strain ranges of 0.7%, 1.2% and 2%. The results will be used in establishing the response of Cu-8 Cr-4 Nb in LCF.

Following testing all test results will be statistically analyzed and confidence intervals determined. The effect of variations between powder production runs will also be quantified. Due to the anticipated complexity of some of the analyses, this work will be partially contracted to RWQS. The data base will be transferred to Rocketdyne and other RLV team members.

Thermophysical Testing

The goal of the thermophysical testing will be to generate design level thermal expansion and thermal conductivity data by the end of FY 00 and transfer that information to Rocketdyne and other RLV participants.

The thermal expansion of Cu-8 Cr-4 Nb from room temperature to 900°C (1652°F) will be determined using an Orton 1600D dilatometer. Cryogenic thermal expansion testing between -196°C (-321°F) and room temperature will be conducted under contract with the Thermophysical Properties Research Laboratory (TPRL) under a small purchase contract funded out of the NASA GRC money to allow accurate modeling of the deformations and stresses within the thrust cell liner. Following testing the average thermal expansion curves and confidence intervals will be calculated.

The thermal conductivity of each production run will be determined using the laser flash method. Because of the specialized equipment and expertise required, this work will be contracted to the TPRL. The testing will give the heat capacity, thermal diffusivity and thermal conductivity between -196°C (-321°F) and 800°C (1472°F).

The work is expected to be completed in early FY 00 and two final reports with the information will be distributed to the RLV program members during FY 00.

Table 1 - Maximum Powder Certification And Database Development Testing Matrix

	Test Temperature (°C)	Samples Per Powder Run	Total Samples
Tensile Strength	**-196**	**3**	**15**
	-40	**3**	**15**
	RT	**3**	**15**
	500	**3**	**15**
	650	**3**	**15**
	800	**3**	**15**
Creep Lives	**500**	**9**	**45**
	650	**9**	**45**
	800	**9**	**45**
Low Cycle Fatigue	**RT**	**9**	**45**
	500	**9**	**45**
	650	**9**	**45**
Thermal Expansion	**-196 to RT**	**3**	**15**
	RT to 900	**3**	**15**
Thermal Conductivity	**-196 to RT**	**3**	**15**
	RT to 800	**3**	**15**

RT = Room Temperature (23°C nominal)

Microstructural Analysis

The goal of the microstructural analysis will be to characterize the initial powder, consolidated material and fracture modes of the Cu-8 Cr-4 Nb during the various mechanical testing that will be conducted by the end of FY 00. The information will be transferred to both Rocketdyne and Crucible Research for future production runs.

In addition to the mechanical testing of the alloy, it is important to characterize the microstructure of the powder and the consolidated materials. NASA GRC is uniquely suited to do so with its Hitachi S-4700 Field Emission Scanning Electron Microscope (FESEM). The FESEM is capable of examining not only prepared specimens, but fracture surfaces at magnifications of up to 300,000 X. The unit also has a backscatter electron detector for imaging compositional differences and an EDAX X-ray chemical analysis system for qualitative and quantitative chemical analyses.

The powder will be characterized to determine the oxides, large Cr_2Nb particles and other inclusions in the starting material. Characterization of the Cr_2Nb precipitate in the powder will be done to determine the degree of precipitate coarsening during processing.

Selected samples of the materials consolidated by extrusion will be examined. The Cr_2Nb precipitate sizes will be compared following processing to determine the particle size in the consolidated materials.

The fracture surfaces of selected tensile, creep and LCF samples will be examined to determine their fracture modes and failure initiation sites. The types and sizes of inclusions found on the fracture surface will give insight into their role in the failure of the material. LCF samples will be examined most closely since LCF tends to find the largest inclusions within the gauge length and hence the one most likely to cause failure in a thrust cell liner.

Integration With RLV Design Work

The Rocketdyne Propulsion and Power Division of Boeing will have responsibility to help determine appropriate test conditions for developing the database. This would primarily involve helping select test conditions that are appropriate to the RLV engine. They will also provide feedback on the database to allow NASA GRC to fill in any gaps in the database being developed for the designers. This would include the types of tests to be conducted during the planning stages and information on the acceptable property ranges as the RLV design evolves. The feedback could also include suggestions for increased numbers of tests if the data for a critical property needs to be better defined. Rocketdyne will also provide a contact point at Rocketdyne that is responsible for ensuring transfer of the information to the appropriate personnel at Rocketdyne. It is anticipated that this person will be Don Ulmer.

Deliverables and Milestones

The primary deliverables for this task will be the database and reports detailing the testing and results. Interim reports and data will be presented as appropriate to Rocketdyne and other RLV participants. In addition, monthly progress reports will be submitted as required to the RLV management. It is anticipated that final reports on each of the tasks listed in Figure 1 will be completed and distributed approximately 3 months after the task is scheduled to end. The database and test results also will be posted to the secure Web server as they become available.

Milestone:	Thermophysical properties database
Date of completion:	January FY00
Output:	Determine the thermal conductivity and thermal expansion of Cu-8 Cr-4 Nb from liquid hydrogen (-253°C) to 900°C
Outcome:	Data will be used for design and trade studies in new thrust cell combustion chamber liners. Current results indicate the 15% lower thermal expansion will result in significant increases in liner lives.

Milestone:	Tensile strength database

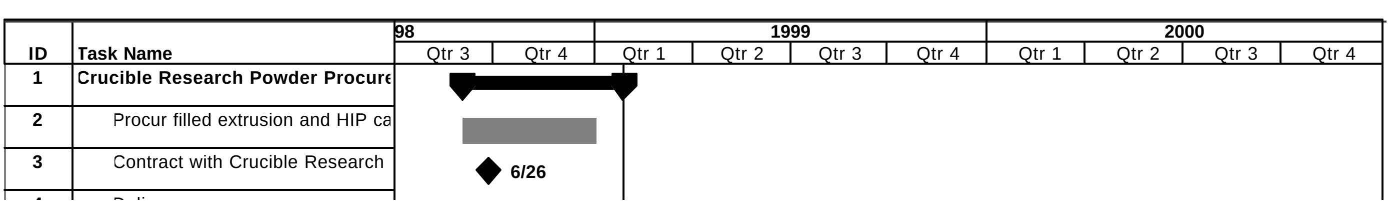
Date of completion: May FY00
Output: Determine the tensile strength of Cu-8 Cr-4 Nb from liquid hydrogen (-253°C) to 800°C
Outcome: Data will be used for design and trade studies in new thrust cell combustion chamber liners. Current results indicate the lower elastic modulus should result in increases in liner lives.

Milestone: Creep properties database
Date of completion: June FY00
Output: Determine the creep strengths and steady-state creep rate of Cu-8 Cr-4 Nb from 500°C to 800°C for creep lives between 5 and 50 hours
Outcome: Data will be used for design and trade studies in new thrust cell combustion chamber liners. Improved creep resistance compared to NARloy-Z should increase liner life.

Milestone: Low cycle fatigue (LCF) properties database
Date of completion: September FY00
Output: Determine the low cycle fatigue lives of Cu-8 Cr-4 Nb from room temperature to 600°C and total strain ranges between 0.7% and 4%
Outcome: Data will be used for design and trade studies in new thrust cell combustion chamber liners. Rocketdyne considers this to be the most critical property for design purposes. Improved LCF lives compared to NARloy-Z will increase liner life.

Milestone: Microstructural characterization of Cu-8 Cr-4 Nb
Date of completion: September FY00
Output: Quantify the microstructure of Cu-8 Cr-4 Nb in all conditions tested
Outcome: Quantifying the microstructure will enable evaluation of microstructure-property relationships. In turn, this will enable improvements in mechanical properties through processing to obtain desirable microstructures.

Milestone: Trade study for substituting Cu-8 Cr-4 Nb for NARloy-Z
Date of completion: September FY00
Output: Conduct a trade study at Rocketdyne to determine the benefits of using Cu-8 Cr-4 Nb in place of NARloy-Z in X-33 and RLV thrust cell liners
Outcome: If sufficient benefits can be shown Cu-8 Cr-4 Nb will be used in place of NARloy-Z for the thrust cell liners



Schedule and Budget

A simplified schedule marking milestones, metrics, and tasks as well as projected NASA FTE requirements is provided below: The official schedule is maintained on the MSFC OPMS.

Activity Name	**FY98**		**FY99**				**FY00**			
Task Milestones and Off Ramps	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Set Cu-8 Cr-4 Nb DOE			▲							
Complete extrusion and machining of Cu-8 Cr-4 Nb samples				▲						
Complete thermal and mechanical testing									▲	
Complete microstructural analysis										▲
Transfer database to RLV designers										▲
Reviews and planning sessions		▲			▲		▲		▲	

Additional personnel consisting primarily of support service contractors and university consortium will also be working on the program as well, but they are not included in these numbers. The table below provides a more detailed explanation of projected expenses.

$K	FY98	FY99	FY00
Powder Certification	183	307	355
Procure 500 pounds of powder in five production runs	100.0	0.0	0.0
Extrude bars for testing	0.0	20.0	0.0
Machine test specimens	0.0	35.0	0.0
Upgrade load frames to strain rate control	40.0	0.0	0.0
Supplies for 60 room and elevated temperature tensile tests	0.0	2.0	5.0
Contract 30 cryogenic temperature tensile tests	0.0	0.0	23.0
Supplies for 135 creep tests	0.0	2.0	5.0
Conduct/contract 135 LCF tests	0.0	5.0	60.0
DOE and statistical analysis contract	3.0	2.0	2.0
Contract with Rocketdyne for support work	0.0	25.0	25.0
Professional personnel support (University Residents grants)	0.0	120.0	130.0
Program Support	10.0	36.0	40.0
FOTS	30.0	60.0	65.0

Thermophysical Testing	17	73	10
Supplies for elevated temp. thermal expansion testing	7.0	1.5	0.0
Cryogenic temperature thermal expansion testing	0.0	30.0	0.0
Contract with TPRL for thermal conductivity testing	0.0	31.5	0.0
FOTS	10.0	10.0	10.0
Microstructural Analysis	5	21.5	35
Field Emission Scanning Electron Microscope usage including technician support	0.0	10.0	25.0
Metallographic preparation	0.0	10.0	10.0
Chemical analyses	5.0	1.5	0.0
Total	**200.0**	**400.0**	**400.0**

Task Management

The Cu-CR-Nb Component Development Team is chartered to certify the RLV Thrust Cell baseline material in the extruded and HIP'd form for use in the RS-2200 thrust cell. This team will use all GRC, MSFC, and support contractor personnel required to ensure success. As a minimum, the following disciplines will be members of the Support Structures CDT:

Team Lead
Material Analysis
Material Test
Design Manufacturing

Appendix 12 Light-Weight Gas-Generator Combustor Assembly

The overall objective of this task is to develop and demonstrate uncooled, hot gas impermeable ceramic composite structures, and deliver a full-scale, lightweight design of a gas generator combustor assembly. The effort is led by NASA GRC teamed with MSFC and Rocketdyne. Ceramic composite development tasks are heavily leveraged from NASA GRC aeronautics and ground-based propulsion programs. By simultaneously addressing the unique processing and properties of ceramic matrix composites and the design requirements of a gas generator combustor assembly, it is expected that a final lightweight, simple design will be delivered that would not be possible with other materials. The demonstration of hot gas impermeable ceramic composite structures would also be applicable to other RLV components such as the thrust cells and nozzle ramp.

This project plan outlines the tasks that will be performed to address the development of lightweight, long life alternatives to the current gas generator assembly design. These tasks were defined to address material, design, and fabrication issues, and to perform appropriate analysis and testing for developing and verifying concepts. Schedule, budget, and personnel aspects for managing this program are also outlined.

Background/Status of Current Technology

For the RLV Aerospike gas generator cycle engine, increasing powerpack performance and reducing its weight can contribute significantly to reducing overall vehicle size and cost by improving engine Isp and reducing overall engine weight. Additionally, the weight of the uncooled metal structures and the system complexity of active cooling are areas which may yield sizable system performance gains if alternative solutions were available. The system simplification implications enabled by the use of uncooled components has the potential to improve the reliability of the RLV.

One technology which may provide the capability to achieve these gains is the utilization of ceramics for primary pressure containment components, such as the GG chamber, the turbine housings and the downstream GG gas exhaust ducting. Ceramic designs for these components would allow the turbines to operate at a much higher temperature, for increased turbine efficiency without the need for complex solutions such as active cooling. This increased turbine efficiency allows the turbine flowrate to be reduced and directly impacts the engine Isp of the gas generator cycle. Additionally, due to their low density and high strength at temperature, these ceramic high temperature components would be significantly lighter than any comparable metal components.

The team of NASA GRC, NASA MSFC, and Boeing-Rocketdyne brings together expertise in ceramic matrix composites, design analysis and system integration to focus on exploiting the potential benefits of a high temperature, light-weight structure. Under the Enabling Propulsion Materials (EPM) portion of the High Speed Research (HSR) aeronautics program, NASA GRC has spent considerable resources (~$200M) developing an large (~60 in dia.) annular ceramic matrix composite combustor. NASA MSFC brings to the table a long, successful history in the design and analysis of combustion devices and turbopump components and an intimate knowledge of testing space propulsion hardware. As the current lead for the Venture-Star propulsion system, Boeing-Rocketdyne's familiarity with the system and system integration aspects of potential new designs is an invaluable resource in taking advantage of new designs and materials developments.

Technical Approach

The technical approach addresses the issues associated with using various non-metallic materials in a gas generator combustor assembly. By simultaneously addressing the unique processing and properties of ceramic matrix composites and the design requirements of a gas generator combustor assembly, it is expected that a final lightweight, simple design will be delivered that would not be possible with other materials. The task will develop and demonstrate uncooled, hot gas impermeable ceramic composite structures, and deliver a full-scale, lightweight design of a gas generator combustor assembly.

The overall technical approach to the gas generator combustor effort is shown in Figure 1. Current problems associated with the implementation of a ceramic or ceramic matrix composite gas generator include permeability, critical flaw tolerance, material degradation, strength, and life performance under the rigorous environments of a gas generator. Key material testing in representative environments (combustion gas, temperature, and mechanical loading scenarios) simulating normal operational as well as transient conditions are planned. Such data will demonstrate the use of ceramics in such an application, provide experience in ceramic design methodologies by anchoring developmental analytical tools, and build confidence for similar component incorporation into RLV and other advanced rocket propulsion systems. The design of a full scale assembly will identify the path for integration into a RLV vehicle.

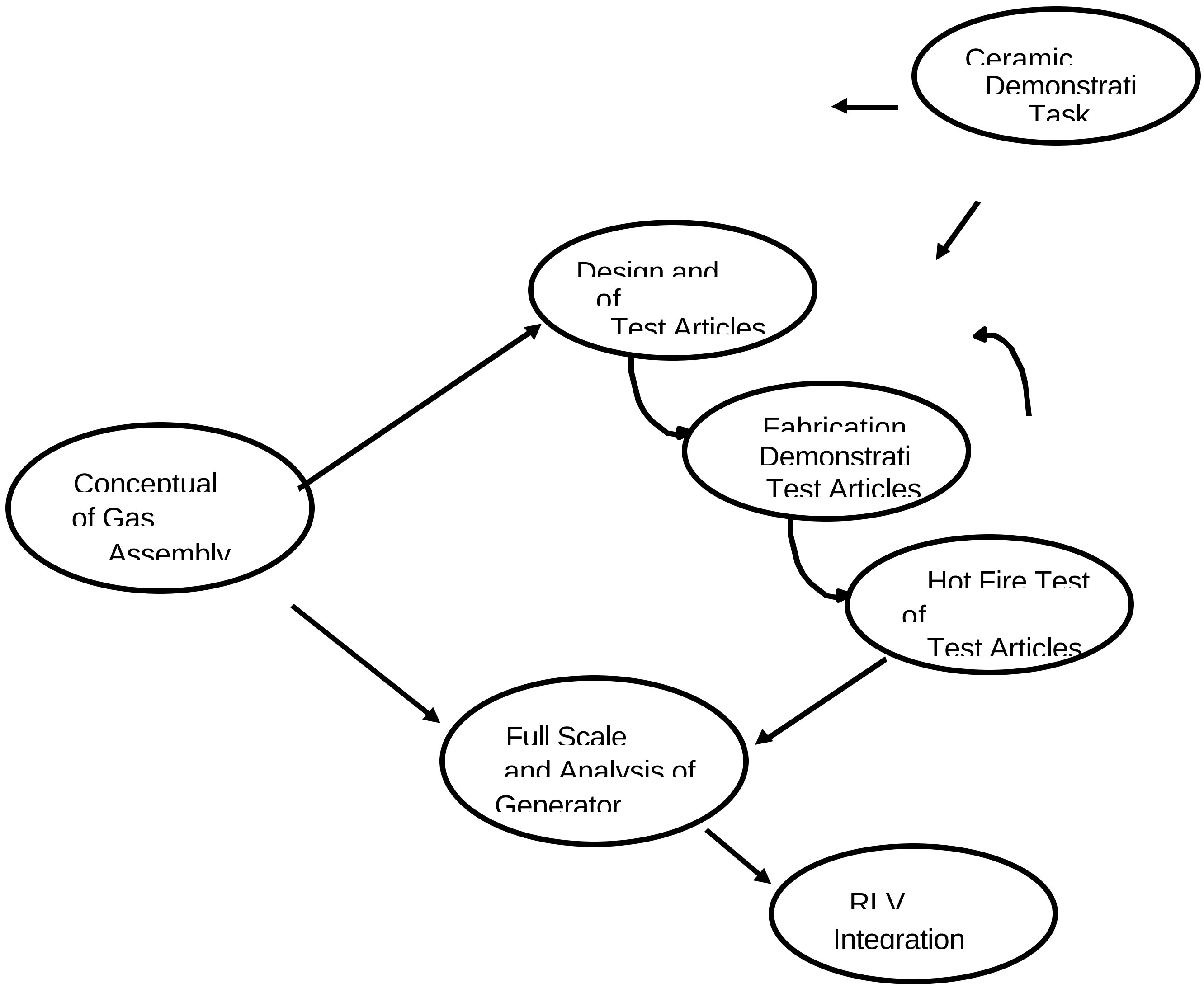


Figure 1. Task flow for development of uncooled gas generator combustor assembly.

In FY98, design requirements will be defined, available technology reviewed, and possible alternate concepts identified. Preliminary joining studies will be initiated. In FY99 and FY00, sub-elements will be fabricated and burst and hot-fire tested. Contracts for material investigation and fabrication demonstrations will be awarded, as required. Appropriate testing and analysis will be performed to resolve issues and demonstrate technologies before selecting the most promising concept. A full scale design and RLV integration plan will be delivered at the end of FY00.

The team combines the efforts and talents of three key organizations within the overall RLV team. This light-weight gas generator combustor assembly task is lead by NASA GRC with a task management team consisting of members from GRC, MSFC, and Rocketdyne. All subtasks are listed below with the lead organization and person identified. GRC is responsible for the program management, materials selection, screening and processing tasks, and sub-element testing. MSFC is responsible for conceptual and detailed designs and analysis and Rocketdyne for supporting the sub-element critical design review and the full scale design.

The specific tasks required to follow this approach have been outlined in further detail.

Scope of Work - Task Breakdown

Conceptual Design of Gas Generator Combustor and Sub-elements
MSFC, with GRC materials support, will develop and rank multiple design options for an uncooled gas generator of the RLV VentureStar size. The options will be analyzed in enough detail to determine strengths and weaknesses of each concept. Additionally, MSFC will design simplified pressure vessel sub-elements to be tested for permeability under simulated operating conditions.

Materials Compatibility Evaluation

Structural/Thermal Evaluation

MSFC will analyze the sub-element designs prior to the Critical Design Review. The analysis will be based on bulk property finite element analysis for thermal and structural issues. Bulk property data for the finite element models will be supplied by GRC. Boundary conditions for models developed will be supplied from the testing/fixture design organization.

Chemical Compatibility Evaluation

GRC will conduct analytical and experimental chemical compatibility studies to assess the potential for degradation of the selected ceramics and ceramic matrix composites in the combustion environment of the RLV gas generator combustor. Analytical models will be those developed under the EPM program to predict recession rates of silicon-based ceramics. Selected experiments will be exposure of coupons to a hot gas combustion environment at applicable temperatures and pressures.

Sub-Element Critical Design Review

Boeing-Rocketdyne will conduct a critical design review of the sub-element components to be burst and hot-fire tested. The primary purpose of the Rocketdyne review is to provide tracability to the RLV.

Ceramic Joining Demonstration

GRC will demonstrate the required joining of ceramics necessitated by sub-element components and final conceptual designs utilizing the Affordable, Robust Ceramic Joining Technology (ARCJoinT) developed by GRC

Sub-Element Fabrication

GRC will fabricate sub-elements in-house using the well established melt infiltration techniques for fabricating silicon carbide components, or purchase sub-elements directly from vendors. Additionally, it is anticipated that combination of purchase and in-house fabrication and joining may be required. A minimum of 12 cylindrical sub-elements will be fabricated. Due to the possibility of multiple processing approaches and the iterative nature of the fabrication-testing cycle, not all sub-elements are expected to be delivered simultaneously.

Sub-Element Testing

Two types of tests will be performed; burst tests and hot fire tests. A minimum of six cylinders (e.g., 2 each from 3 fabrication approaches) will be burst tested at room temperature. Burst testing will be performed under contract at an appropriate testing facility. Additionally, a minimum of six sub-elements will be hot fired in a GRC test stand. Chemical, thermal and mechanical conditions will simulate those expected in the final gas generator assembly.

Non-Destructive Evaluation

Ultrasonic c-scan, thermal imaging, and radiography will be used to qualify six ceramic-CMC-ceramic cylinders before burst tests. For the other six cylinders which will undergo hot firing, extensive NDE will be done before and after firing. The NDE will consist of high resolution ultrasonic , thermal, and x-ray imaging, acoustic-ultrasonic decay measurements, and x-ray computed microtomography slices of the middle five-inch section. A digital 3-D representation of the middle section will be generated. Correlation between damage states as detected by NDE, structural modeling including NDE findings, and experimental test conditions will be established.

Full Scale Design

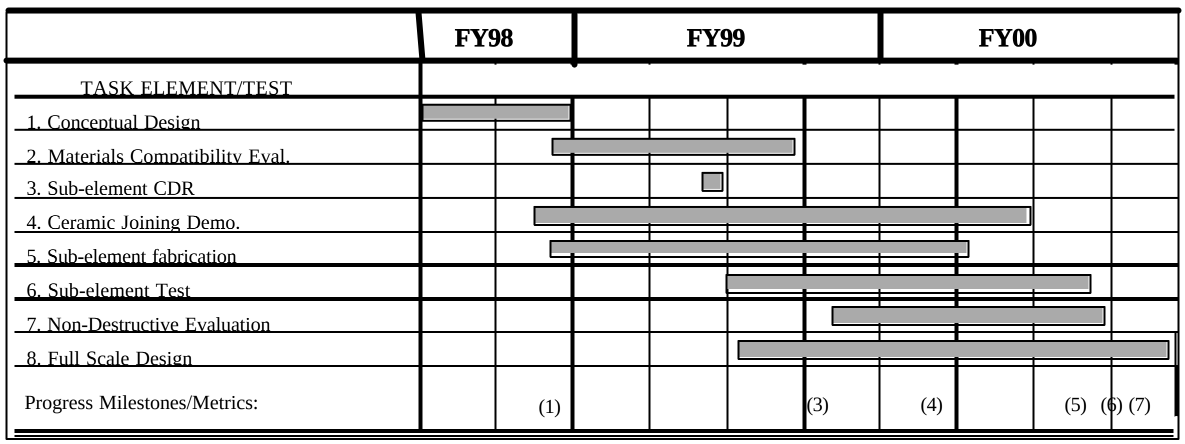
A full scale design will be developed based on the Venture Star power balance at the time the design effort begins. The intent is to develop a design that can be implemented in the Venture Star powerpack with as minimal modifications as possible. However, the design is not restrained to be a direct retrofit due to the variations in design restrictions between the metallic and ceramic materials. The design will be completely analyzed to ensure the design is usable.

Task Management

Light-weight, High Performance Gas-Generator Development Team This team is chartered to develop develop and demonstrate uncooled, hot gas impermeable ceramic composite structures, and deliver a full-scale, lightweight design of a gas generator combustor assembly. The effort is led by NASA GRC teamed with MSFC and Rocketdyne. This team will use all GRC, MSFC and support contractor personnel required to ensure success.

Integrated task Schedule and milestones

A task and milestone schedule is shown below:



Task Milestones

Conceptual design selection
Materials compatibility defined
Sub-element geometry defined
Requisite sub-element joining approach demonstrated
Sub-elements fabricated
Sub-elements burst and hot-fire testing completed
Full scale design completed

Schedule and Budget

The projected schedule, funding requirements, and NASA FTE requirements are shown below:

Activity Name	**FY98**		**FY99**				**FY00**			
Task Milestones and Off Ramps	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Conceptual Design Selected			▲							
Materials Compatibility Defined						▲				
Subelement Defined							▲			
Subelement burst and hot-fire tests completed									▲	
Full Scale Design										▲
Reviews and planning sessions		▲			▲		▲		▲	
Task Elements										
1. Conceptual Design of Combustor Assembly and Sub-elements										
GRC (FTE)	0.2	0.2								
MSFC (FTE)	0.7	0.8								
Funds Required ($k)		60								
2. Materials Compatibility Evaluation										
GRC (FTE)		0.1	0.05	0.05	0.05	0.05	0.05	0.05		
MSFC (FTE)		0.2	0.05	0.05	0.05					
Funds Required ($k)		5	39	39	38		19			
3. Sub-Element CDR				■						
GRC (FTE)				0.2						
MSFC (FTE)				0.1						
Rkdne ($k)				35						
Other Funds Required ($k)				10						
4. Ceramic Joining Technology										
GRC (FTE)		0.1	0.05	0.05	0.05	0.05	0.1	0.1		
Funds Required ($k)		40	30	30	15	7	60	42		
5. Sub-element Fabrication										
GRC (FTE)			0.05	0.05	0.05		0.1			
Funds Required ($k)			30	30	20	7	60	38		
6. Sub-element Testing										
GRC (FTE)			0.2	0.1	1.1	1.1	1.1	1.1	.9	
Funds Required ($k)			110	120	70	58	140	140	123	

7. Non-Destructive Evaluation										
GRC (FTE)						0.1	0.1	0.1		
Funds Required ($k)						20	16	16		
6. Full Scale Design										
GRC (FTE)					0.1	0.1	.08	.08	.08	.06
MSFC (FTE)					0.6	0.7	0.6	0.6	0.6	0.6
Rkdne ($k)					35		60			
Other Funds Required ($k)					40	35	32	32	32	30
Total Funding Required ($k)		105	209	264	218	127	387	268	155	30

	FY98	FY99	FY00	Total
GRC Total FTE	0.6	3.6	4.2	8.4
GRC Prog. Support ($k)	24	144	168	336
MSFC Total FTE	1.7	1.4	2.8	5.9
MSFC ED FTE	0.75	0.4	1.5	2.65
MSFC EP FTE	0.85	0.7	1.0	2.55
MSFC EH FTE	0.1	0.3	0.3	0.7
MSFC Prog. Support ($k)	31	25	50	106
Rkdne ($k)		70	60	130
GRC Materials and SSC ($k)	40	577	563	1180
MSFC Materials ($k)	9		13	22
Total ($k)	104	816	841	1761

REVIEWS

Program/progress reviews will be conducted on a regular basis. Written monthly technical and financial progress reports will be provided. The task shall also support annual reviews to the Space Transportation Lead Center Program Management Council and an independent annual NASA review. A final report detailing the progress of the program will be provided.

A conceptual design review (CDR) will be conducted on the sub-element test articles after requirements have been defined, available technology has been reviewed, and materials have been investigated.

A detailed test plan and test matrix will be compiled to establish the required hot-fire test program.

Deliverables

In addition to required material samples and fabrication demonstration components, this program will provide a full scale design of the gas generator combustor assembly.

Appendix 13 Polymer Matrix Composite Lines, Valves and Ducts

The Access to Space Study identified the requirement for lightweight structures to achieve orbit with a single stage vehicle. The use of composite components partially fulfills that requirement. The purpose of this task is to extend previous efforts with polymer matrix composite (PMC) lines, and develop additional technology for application to PMC valve housings. This project plan identifies activities, deliverables, participants, and key milestones for this task. This plan will be updated significantly during the project planning phase of this task.

Overview/Procedure

MSFC will fabricate lines and valve housings under this project for testing in LH2 and LOX environments. Several key technologies will be demonstrated in the ducts. These include scalability, composite flanges, flange sealing, ability to build complex geometries, one piece fabrication, reparability, and low cost tooling. A composite valve housing as a replacement unit for an existing valve design will be designed and fabricated by a selected valve supplier, and will be tested at MSFC.

Additional lines will be fabricated using alternate materials and processing methods, including electron-beam curing coordinated through Oak Ridge National Laboratory (ORNL) and solvent-assisted resin transfer molding (RTM) processing coordinated through GRC.

The materials used in this project will be characterized to obtain mechanical, physical, and damage tolerance properties. Repair and inspection methodologies will be developed for the lines.

Deliverables

Deliverables include several approximately eight inch diameter lines, from MSFC and from GRC, with e-beam curing provided by ORNL. The number of lines to be fabricated will be determined in the project planning phase, based on detailed design, fabrication, and test requirements, and based on project funding levels.

Two or more approximately eight inch diameter valves will be provided by a valve supplier to be selected during the project planning phase, based on project funding levels.

Benefits

The most obvious benefit derived from the development of PMC components is the reduction in weight, and thus the opportunity for increased performance. In addition, the use of PMC materials in many cases leads to a reduction in the numbers of assembled parts, and as a result, leads to reduced manufacturing costs.

Participants And Responsibilities

MSFC Project coordination, materials selection, design, analysis, fabrication, test, and multiple cross-cutting activities.

GRC Materials selection, fabrication, and possibly test support.

ORNL Materials selection, e-beam curing.

Objectives

The primary objective of this effort is the demonstration of PMC components in cryogenic (LH2 and LOX) environments. Secondary objectives include scalability of PMC components, demonstration of seal systems on PMC surfaces, LOX compatibility of PMC materials, and damage tolerance and repair of PMC materials.

Approach

The effort will focus primarily on the design, analysis, fabrication, and test of approximately 8-in. diameter composite lines by a multi-disciplinary Component Development Team (CDT) comprised of personnel from Marshall Space Flight Center (MSFC), Glen Research Center (GRC), Oak Ridge National Laboratory (ORNL), and one or more component suppliers to be selected early in the project.

MSFC has several composite lines that have been fabricated under a previous project. At least two of these articles will be tested using LN2, and the results of those tests will help determine the path to be taken for the remainder of the effort.

MSFC will fabricate lines under this project for testing in LH2 and LOX environments. Several key technologies will be demonstrated in the ducts. These include scalability, composite flanges, flange sealing, ability to build complex geometries, one piece fabrication, reparability, and low cost tooling. A composite valve housing as a replacement unit for an existing valve design will be designed and fabricated by a selected valve supplier, and will be tested at MSFC.
Additional lines will be fabricated using alternate materials and processing methods, including electron-beam curing coordinated through Oak Ridge National Laboratory (ORNL) and solvent-assisted resin transfer molding (RTM) processing coordinated through GRC.

The materials used in this project will be characterized to obtain mechanical, physical, and damage tolerance properties. Repair and inspection methodologies will be developed for the lines. Key products to be developed are multi-bend composite lines with integral flanges and composite valve housings.

Go/No-Go Points And Milestones

Estimated resource requirements will be updated at the end of the project planning phase and annually at fourth quarter reviews. Those updates will be used as a basis for decisions on numbers of test articles that remain to be fabricated and/or tested. In particular, the fabrication and test of a composite valve housing will be reduced and/or eliminated prior to the reduction and/or elimination of composite lines. LOX compatibility results and LH2 permeability results will also be key to go/no-go decisions with regards to component demonstration testing.

Key milestones for the project are the completion of fabrication of test articles, and the completion of demonstration tests of those articles.

Statement Of Work

This Statement of Work (SOW) describes the requirements for the design, analysis, fabrication, and test of polymer matrix composite (PMC) ducts and valve housings for application to a reusable launch vehicle propulsion system.
Tasks to be completed in this effort consist of design, analysis, fabrication, and test of PMC components. A project planning task will be conducted at the project outset to define requirements and to develop detailed task plans for all activities. Cross-cutting tasks include material characterization, oxygen compatibility, hydrogen permeability, damage tolerance and repair, and nondestructive evaluation. All tasks are iterative and will occur concurrently to a very large extent.

Project Planning

Detailed plans for all activities to be conducted will be developed during the project planning phase. Design requirements, including operating environments and geometries, for a duct and valve housing will be determined, based on requirements for VentureStar. Materials will be screened for applicability, and for potential e-beam curability. Test requirements for PMC articles will be developed based on the selected design and performance requirements. Tooling requirements for multiple processing methods will be examined, and optimum low-cost tooling methods will be selected during this phase of the project.

Design

PMC ducts have been fabricated under a previous project, using an existing design from MSFC Propulsion Laboratory (EP). The design incorporates integral PMC flanges and associated seal systems. The design will be reviewed by the CDT and will be modified as needed to incorporate specific needs of the various team members, and will then be used for the fabrication of additional ducts for testing under this project.

Available valve housing designs will be reviewed by the CDT, and one design will be selected and modified as needed for the application of PMC materials. The valve housing design review and modification will include at least one valve supplier, to be selected during the project planning phase of this effort.

Detailed plans for designs and design modifications will be developed during the project planning phase of this effort. Some flexibility will be exercised to allow for the application of multiple materials and/or processing methodologies.

Analysis

Static structural analysis of the design has been provided by MSFC Structures and Dynamics Laboratory (ED) under the previous project. Static and dynamic structural analyses of the design as modified by the team will be provided by MSFC ED and will be reviewed by the team.

Detailed plans for analyses will be developed during the project planning phase.

Fabrication

Ducts will be fabricated by MSFC Materials and Processes Laboratory (EH) and GRC. Ducts fabricated by MSFC EH will be autoclave cured. Ducts fabricated by GRC will be processed using resin transfer molding (RTM). ORNL will provide e-beam curable materials to MSFC to support fabrication and ORNL will coordinate electron beam (e-beam) curing. These lines will be compared to others fabricated using traditional thermosets and autoclave curing.

Valve housings will be fabricated by a supplier to be selected during the project planning phase.

Detailed fabrication plans will be developed during the project planning phase.

Test

A rigorous test series will be performed on the test articles to determine the merits of the design and fabrication techniques. Planned tests by MSFC EP (and ED, as noted) include:

LH2 and LOX Composite Ducts: Testing on these ducts will include proof pressure, leakage (at room and cryogenic temperatures), thermal and pressure cycles with, strength tests at cryogenic temperature (ED), cryogenic vibration test (EP), and burst pressure.

Seal Evaluation: Testing will evaluate the use of existing seal designs for sealing composite flanges. Several seal designs will be purchased from seal manufactures. Leakage tests will be performed at MSFC under maximum operating pressure and under cryogenic and room temperatures.

Composite Valve for LH2 Service: Testing on these valves will include proof pressure, leakage (at room and cryogenic temperatures), thermal and pressure cycles, functional, strength tests at cryogenic temperature (ED), cryogenic vibration test (ED), and burst pressure.

Detailed test plans will be developed during the project planning phase.

Cross-Cutting Activities

Multiple activities will be conducted in support of the primary objective of this effort. Included are material characterization, oxygen compatibility, hydrogen permeability, damage tolerance and repair, and nondestructive evaluation. These activities will be conducted concurrent to other tasks, to achieve schedule optimization.

Material Characterization

Materials from MSFC, GRC, and ORNL will be subjected to a series of basic material characterization tests by MSFC EH. Tests include mechanical properties such as tension, compression, shear, and coefficient of thermal expansion; and physical properties such as density, fiber volume, and void content.

In addition, ORNL will provide material screening for the selection of e-beam curable resins that may meet LOX compatibility and other project requirements.

Detailed test matrices will be developed during the project planning phase.

Oxygen Compatibility

Materials from MSFC, GRC, and ORNL will be subjected to oxygen compatibility testing. PMC materials clearly fail flammability tests; therefore, evaluation for safe use of composite materials relies on accurate assessment of potential ignition sources beyond the standard mechanical impact test, currently used to qualify materials. The qualification of composite materials for use in LOX environments is planned to follow a phased testing approach by MSFC EH. Phase I is used to down-select candidate materials by use of the standard mechanical impact test. Phase II (coupon testing) will include puncture, electrostatic discharge, friction, cryopumping simulation, pyrotechnic shock, modified mechanical impact, particle impact, and crack propagation testing. Candidates passing the coupon tests will be evaluated at the sub-scale component level. Phase III (sub-scale component testing) will be simulated environment testing of sub-scale feedlines. Testing on sub-scale components will include vibration, vibration with debris, acoustic environment, and burst testing. Phase IV (component testing) large-scale component testing will be conducted as necessary.

Detailed test matrices will be developed during the project planning phase.

Hydrogen Permeability

Materials from MSFC, GRC, and ORNL will be subjected to hydrogen permeability testing. Hydrogen permeability is a key element in the development of PMC components. Permeation of hydrogen at room and cryogenic temperatures and at multiple pressures will be evaluated on the PMC materials that are selected for fabrication.

Detailed test matrices will be developed during the project planning phase.

Damage Tolerance And Repair

Selected PMC materials will be subjected to multiple levels of impact damage by MSFC EH to assess damage tolerance. An instrumented drop-weight impact tester will be used to subject coupons to varying levels of damage. Coupons will be examined post-test to verify damage modes and regions. Additionally, some coupons will be subjected to mechanical tests to determine residual strengths post-impact, and others will be subjected to tentative repair methods and then subjected to mechanical tests to verify improvements in residual strengths due to repair.

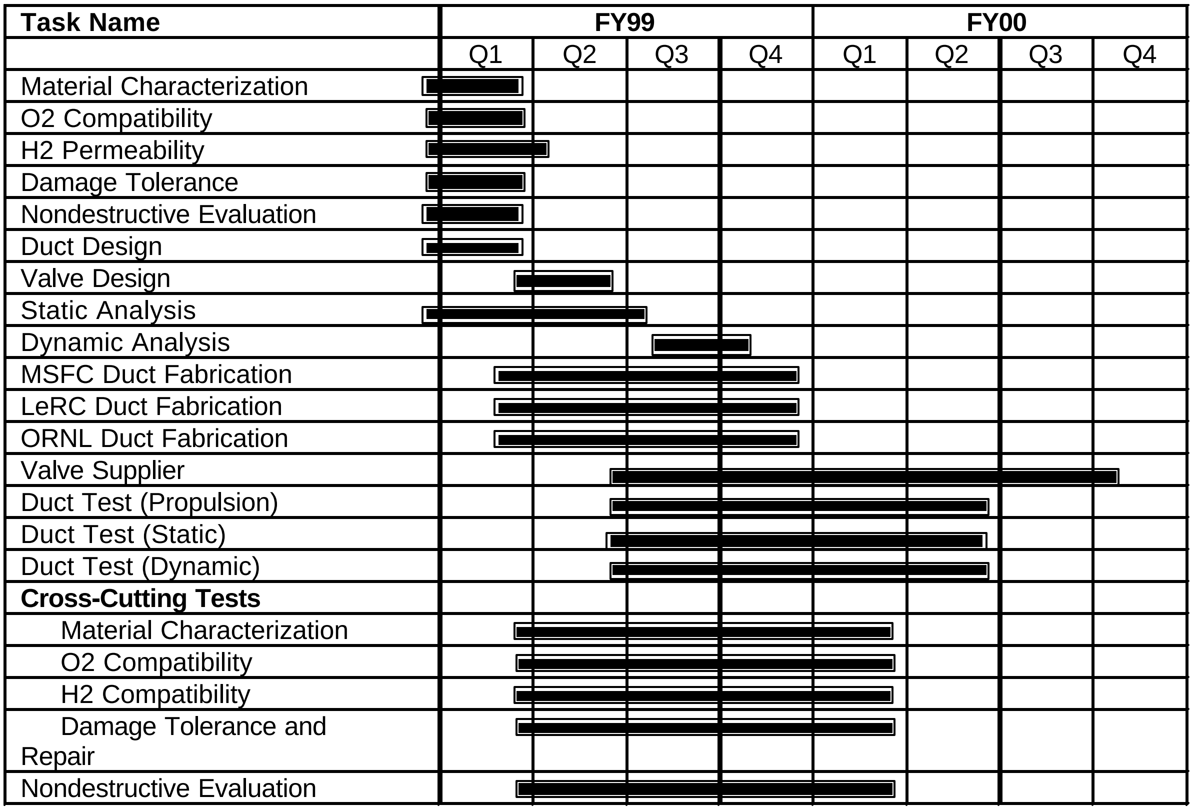
Nondestructive Evaluation

The fabrication of multiple articles necessitates the use of nondestructive evaluation techniques to verify part consolidation. Nondestructive evaluation will be provided by MSFC EH - capabilities include UT, industrial CT, AE, ET, X-radiography, Thermography, and Shearography. NDE will be employed across multiple tasks from the coupon level to the component level for each of the material systems and components that are developed under this project.

Schedule and Budget

The projected schedule, funding requirements, and NASA FTE requirements are shown below:

Resources	FY99	FY00
C. S. FTE		
EH	2.0	2.0
EP	2.5	3.0
ED	0.2	1.0
LeRC	1.0	2.0
Total	**5.7**	**8.0**
Cost ($K/yr.)		
MSFC	379	512
ORNL	110	75
LeRC	200	250
Subcontractors	240	90
Total	**929**	**927**



Task Management

This team is chartered to develop a lightweight PMC Lines and Valve technologies using the projected RS-2200 Aerospike operating conditions as the design conditions for the effort. Key opportunities for weight reduction and performance enhancement are in innovative use of polymer matrix composite materials and advanced manufacturing techniques. The team will be responsible for meetings the requirements of the test facility and providing a safe test article for the project. This team will use all MSFC and support contractor personnel required to ensure success. As a minimum, the following disciplines will be members of the Tankage Structures CDT:

Team Lead Structural
Design Stress Analyst
Thermal Analyst
Material Selection Specialist
Manufacturing Specialist
NDE Specialist
Materials Test Specialist
Propulsion Test Specialist

Appendix 14 High Head Unshrouded Impeller Technology

Marshall Space Flight Center (MSFC) has been actively involved in the design and testing of high performance pump elements since 1988. Jointly with Rocketdyne (and other entities) we designed and tested an advanced, high head shrouded impeller designed to allow a two stage fuel pump for the now canceled Space Transportation Main Engine (STME). This would have led to lower manufacturing cost and increased engine thrust-to-weight (T/W) ratio over the baseline 3-stage design. The Reusable Launch Vehicle (RLV) will require higher T/W ratio engines than currently available. One of the key technologies that will enable significant improvements in T/W ratio is advanced unshrouded impeller technology. Unshrouded impellers have been used in rocket engines in the past primarily because they can be manufactured less expensively than shrouded impellers. However, unshrouded impellers also have a structural advantage over shrouded impellers. The use of unshrouded impellers allows for higher tip speeds and, hence, greater pressure rise per pump stage (increased stage loading), resulting in the reduction of turbopump size and weight.

Table 1 - Weight Savings Potential for SSME ATP HPFTP

	Shrouded	Unshrouded
Pump efficiency (%)	78.6	76.3
Pump horsepower	75670	78600
Impeller tip speed (ft/sec)	1890	2321
Head coefficient	.558	.552
Stage loading (feet of head)	61145	92390
Pump stages	3	2
Turbopump weight (pounds)	990	490

Table 1 illustrates the potential benefits of the increased stage loading (possible with unshrouded impellers) for the Space Shuttle Main Engine (SSME) Alternate Turbopump (ATP) high-pressure fuel turbopump (HPFTP). Note that there is a potential weight savings of 490 pounds to the ATP HPFTP if advanced unshrouded impellers are used.

Marshall Space Flight Center has been working on developing this technology for a potential upgrade to the SSME. Extensive design parametrics have been performed on impellers designed to meet the SSME HPFTP pumping requirements. This effort has resulted in an impeller design that does meet the pumping requirements for a two stage SSME HPFTP. The resulting impeller design's performance will be verified at MSFC's pump test equipment (PTE) facility in a impeller test rig especially designed to facilitate testing of unshrouded impellers.

The current VentureStar engine balance requires a cumulative pressure rise through the fuel pump impellers of approximately 5600 psi (196,000 ft). Use of state-of-the-art (SOA) shrouded impeller technology and materials limits the stage loading to approximately 70,000 ft/stg. This results in a three-stage pump design for the VentureStar. An impeller with a stage loading of 105,000 ft/stg would allow a two-stage pump design and significantly reduce the pump size and weight. Under the SSME HPFTP unshrouded impeller technology task previously discussed, 95,000 ft/stg was achieved using currently available materials. This program will extend the technology to make it possible to achieve the required 105,000 ft/stg for the VentureStar RLV engine balance without sacrificing pump efficiency.

Due to the lack of maturity in the RLV fuel pump design it is not possible to definitively quantify the weight savings potential if unshrouded impellers are used. Based on the horsepower required by the pump and historical correlation, the baseline 3-stage turbopump should weigh approximately 1200 lb. Assuming a similar weight reduction for the 2-stage VentureStar turbopump as is predicted for a 2-stage SSME ATP HPFTP pump, then potentially a 600 lb. weight reduction is possible per turbopump for a total potential weight reduction of 4200 for the seven turbopumps required in the VentureStar propulsion system.

Objectives

The objective of the present program is to extend the work already underway at MSFC on unshrouded impellers and apply the technology to the RLV fuel turbopump. Since the SSME is a stage combustion cycle engine, for a constant chamber pressure the engine specific impulse, Isp, is not sensitive to pump efficiency. The Isp of a gas generator cycle (chosen for the RLV main propulsion system) is sensitive to pump efficiency. It is established that the efficiency of unshrouded impellers is affected by tip clearance. However, the data available is for impellers with significantly less stage loading. Therefore, the first objective for this program is to experimentally determine the sensitivity of the efficiency of the SSME design point impeller to tip clearance variation. The second objective is to then develop a design, using the latest analytical techniques and experimental data, an unshrouded impeller that will meet the performance requirements of the RLV engine with a 2-stage pump design. The third objective is to test this resulting design in the MSFC water rig and verify its performance. The final objective is to produce a conceptual, two-stage design of the RLV fuel turbopump that incorporates the verified unshrouded impeller design in this program. Based on results obtained in a study of the SSME HPFTP, this could yield as much as 50% reduction in weight per turbopump, currently projected to weigh 1200 lbs. each. Assessing tip clearance affects on efficiency and extending the design database to 105,000 ft/stg are the key technology needs required for meeting these objectives.

Technical Considerations

There are a few technical considerations that merit a short discussion before proceeding with the task descriptions. (1) It is the intent of the program to design with readily available materials. Should higher capability materials become available during the course of completing the project then they will be considered. (2) As currently structured, this program will not investigate advanced rotor axial position control schemes. It is assumed that the resulting conceptual design will incorporate either an active balance piston or a hydrostatic axial bearing. (3) Limitations on rotational speed imposed by turbine structural considerations or by suction specific speed may reduce the potential weight savings. Suction specific speed limitations can usually be overcome by designing a low-speed pump stage. Turbine speed limitations can be addressed in many ways. The PI for this program is aware of the RLV turbine development program and the NRA 8-21 Turbine Performance Optimization program. He will remain informed of the progress made in these programs for the purpose of assessing potential impacts to the present program. Furthermore, the TP conceptual design activity will be initiated early in the program and continuously updated with the latest analytical and experimental results. Therefore, the impact of these technical considerations will be continuously under consideration and, if warranted, program change requests will be generated to maximize the benefit derived from this effort.

Scope of Work

There are four major tasks required to develop the technology and meet the weight reduction objectives. (1) The affect of tip clearance on high head coefficient impellers performance will be determined experimentally using the SSME HPFTP design point impeller. (2) Using the latest available analytical techniques and experimental data an impeller design will be developed that will allow a 2-stage RLV fuel pump. (3) This optimized design will be tested in the impeller technology rig at MSFC to verify its performance. (4) Finally, a conceptual design of a 2-stage RLV fuel pump will be generated. Table 2 shows the schedule and cost associated with each task. In addition to the reports generated at the completion of each major task, a final document will be generated at the conclusion of this program that will summarize the entire program and provide recommendations for future activities. MSFC will be responsible for generating this final report with Rocketdyne support.

Tip Clearance Assessment

The impeller technology rig will be used to determine the effect of tip clearance on the performance of high stage loading impeller. The testing will be done using the impeller technology rig (figure 1). The rig has been designed such that tip clearance can be adjusted by removing the inlet housing and placing the appropriately sized shim between the inlet housing and the stationary shroud. Allowance has been made in the rig design for the testing of the impeller with or without a vaned diffuser, for testing of impellers of various profile shapes, and for testing with various inlet velocity profiles. The rig is extensively instrumented such that the performance of the impeller can be measured directly rather than having to rely on the more common flange-to-flange performance measurements. A minimum of three tip clearances will be tested. The results of this testing will be documented in the form of a post test report for use in subsequent tasks. MSFC will have responsibility for this task.

RLV Unshrouded Impeller Design

The latest available design tools and experimental data will be used to develop an unshrouded impeller design that meets the performance requirements of a 2-stage RLV fuel pump. Rocketdyne will be responsible for generating the hydrodynamic definition for the impellers, for assessing the structural viability of the proposed designs, and for assuring the projected operating point does not violate constraints imposed by other turbopump subcomponents. MSFC will be responsible for performing detailed analyses of the proposed design at nominal and off-nominal tip clearances. Rocketdyne will support MSFC with detailed analyses and will be responsible for predicting the rotordynamic coefficients of the unshrouded impeller. A minimum of five designs will undergo detailed analysis. MSFC will document the results of the design parametrics with Rocketdyne support.

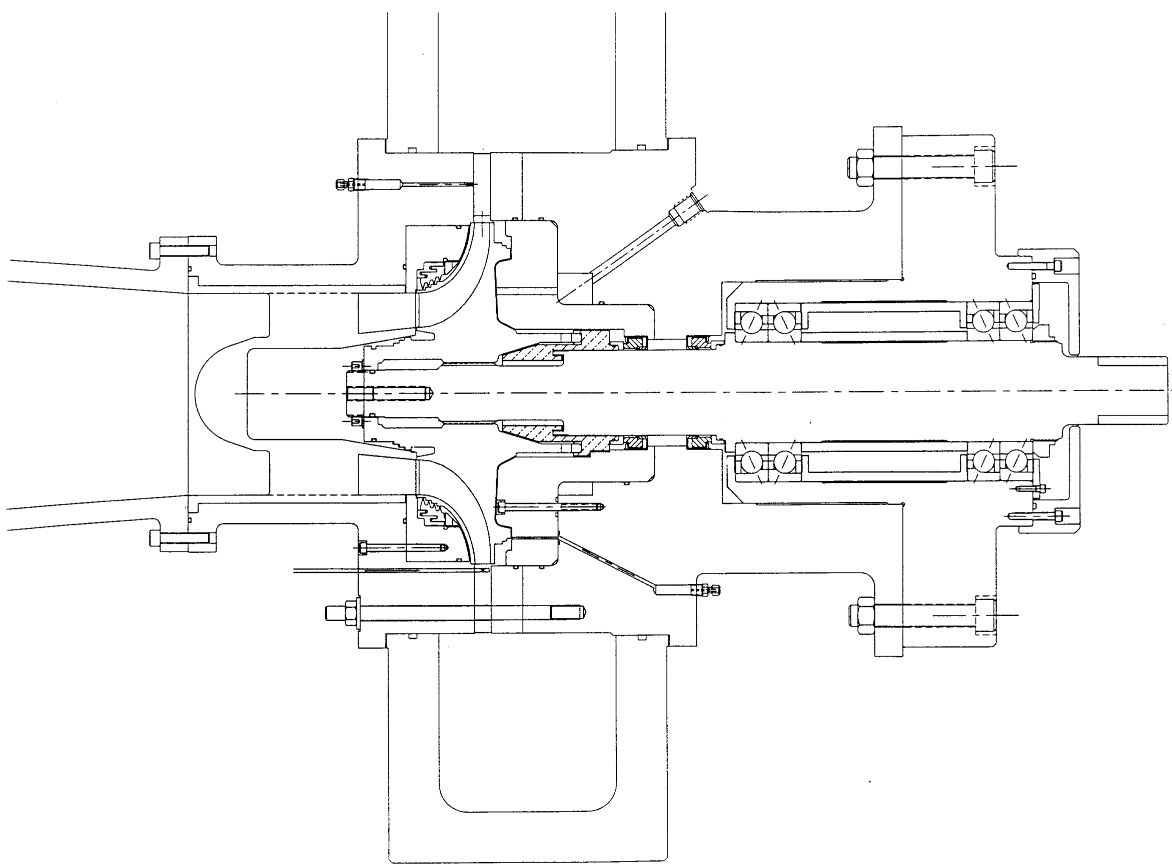
RLV Unshrouded Impeller Testing

The performance of the resulting impeller design will be verified through testing in the impeller technology rig at MSFC's Pump Test Equipment (PTE) facility. The rig hardware will be modified to accommodate the impellers profile and testing will occur at a minimum of three different tip clearances. A post-test report will be issued documenting the test results. MSFC will be responsible for this task.

Two-Stage Pump Conceptual Design

In order to quantify the benefit derived to the RLV engine system, The final impeller design will be integrated into a conceptual pump design. In addition to quantifying the benefits, this conceptual design will be the basis for a detailed design should the program choose to proceed with this concept and demonstrate it at the turbopump level. The results of this task will be documented in the form of a conceptual layout drawing of the 2-stage pump and a report that discusses to appropriate depth specific turbopump design issues as suction performance, rotordynamics, required turbine structural and aerodynamic performance viability, estimated manufacturing cost, and estimated weight. Rocketdyne will be responsible for this task.

Figure 1 - Impeller Technology Rig



Task Management

MSFC has formed a CDT with RKDN to design, analyze, and test high head unshrouded impellers using the projected RS-2200 Aerospike operating conditions as a design condition. MSFC will lead the team's activities and will be responsible for all rig testing, detailed flow analyses, and final documentation. RKDN will be responsible for the hydrodynamic design, structural assessment, impeller rotordynamic coefficient prediction, and conceptual design of the 2-stage RLV fuel pump. The schedule and costs against which the team's progress will be compared is shown in Table 2.

All required government personnel will be from the Fluid Dynamics Division of the Structure and Dynamics Laboratory. The principal investigator for this project is Robert Williams of MSFC's MSFC . Mr. Williams will be responsible for coordinating the activities of the MSFC-RKDN team and for conducting MSFC's flow analysis. Stephen Skelley from MSFC is currently assigned to be the test engineer for this program, and, will be responsible for coordinating all testing activities. George Prueger will be the Rocketdyne lead and he will be responsible for coordinating the work to be performed at Rocketdyne.

Reporting and Reviews

A monthly report will be submitted describing program progress and identifying issues. There will be a kick-off meeting at program initiation to present the program and to assure that no issues have arisen since the proposal was submitted. There will be pre- and post-test meetings for both testing tasks. There will be a telecom at least bi-weekly during the design iteration process to status the progress. The PI and the Rocketdyne lead will discuss program process at least bi-weekly. There will be a review early in the fourth quarter of FY99 to assess a potential program off-ramp. A final presentation of the program results will be made to MSFC program management, chief engineers office, and the prime RLV contractor.

Budget and Schedule

The projected schedule, funding requirements, and NASA FTE requirements are shown in Table 2 below:

Activity Name	FY98		FY99				FY00			
Task Milestones and Off Ramps	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Set 2-Stage Pump Design Point					▲					
Go/No-Go Rig Testing (Off-Ramp)						▲				
Complete Rig Modifications								▲		
Complete 2-Stage Pump Design										▲
Task Elements										
1. Tip Clearance Sensitivity Tests										
MSFC (FTE)		0.2	0.9							
Rig Mods, test support (RECOM)		55K								
2. RLV Impeller Design Optimization										
MSFC (FTE)		0.1	0.5							
RKDN		45K	60K							
MSFC Computer Upgrade			35K							
3. Prep. for RLV impeller testing										
MSFC (FTE)					0.1		0.1			
Rig/Facility Mods (RECOM)					90K		40K			
4. RLV Unshrouded Imp. tests										
MSFC (FTE)								1.2		
Testing Support (RECOM)							30K			
5. RLV 2-Stage Pump Design Concept										
RKDN					30K			55K		
6. Documentation										

Year by Year Totals	**Total**	FY98	FY99	FY00
MSFC (FTE)	4.0	0.4	1.9	1.7
MSFC FTE Costs	69K	6K	31K	32K
RKDN	190K	45K	90K	55K
Rig Sub and Material	250K	55K	125K	70K
Total Cost	509K	106K	246K	157K
Funding Shortfall				

In order to maintain the submitted schedule, there are three significant milestones that need to be met (Table 2). The 2-stage pump design points needs to be set by the start of the third quarter of FY99 (April 1999) in order that rig and facility modifications can proceed. Failure to meet this milestone will require that the rig and facility modification time be compressed in order to complete the task prior to the end of FY00. The second milestone requires that 2-stage pump impeller testing be underway by the middle of the second quarter of FY00 such that test results can be incorporated into the conceptual pump design. The final milestone requires completion of the conceptual design by the middle of the fourth quarter of FY00.

In the fourth quarter of FY99 there is a natural potential off-ramp in the program. By this time the 2-stage pump impeller design will be completed and a preliminary assessment of the benefits to the engine will have been made. This will allow for an assessment to be made as to whether the defined benefits warrant proceeding to rig testing and to completion of conceptual pump design. The participants will provide a recommendation with justification to the MSFC program and Chief Engineers Office.

Deliverables

In addition to the intermediate and final reports that will document this activity, this program will provide a conceptual pump design and a detailed impeller design with quantified benefits, if implemented, to the RLV engine system. Furthermore, advanced tools that are verified under this program (such as an unshrouded impeller rotordynamic coefficient prediction model) would be available for application to any future program. Finally, our design space will be enlarged to higher stage loading than currently available with the addition of analytical and experimental data.

Appendix 15 Turbine Performance Optimization Technology Task

The Reusable Launch Vehicle (RLV) requires a high value of specific impulse (I_{sp}) and a high thrust to weight ratio. These requirements have necessitated compact, high power turbine designs. Turbine power is produced through a combination of its mass flow rate and work per pound of fluid. The RLV engine is a gas generator cycle where propellant is tapped off of the main engine flow to provide the drive gas for the turbine. At the exit of the turbine, the drive gas is dumped overboard and does not contribute to engine thrust. Therefore, for a gas generator cycle, the mass flow rate through the turbine is a direct loss to engine I_{sp} and must be minimized, and power must be produced predominately through high work. To obtain high work, the available energy of the gas must be increased, or the turbine must extract energy from the gas more efficiently.

Weight Savings Potential for the SSME ATP HPFTP

	Shrouded	Unshrouded
Pump efficiency (%)	78.6	76.3
Pump horsepower	75670	78600
Impeller tip speed (ft/sec)	1890	2321
Head coefficient	.558	.552
Stage loading (feet of head)	61145	92390
Pump stages	3	2
Turbopump weight (pounds)	990	490

The RLV program has chosen the first option by supplying a high turbine inlet temperature. This decision has spawned a materials development program for ceramics, since uncooled metals cannot withstand the temperature. The viability of the ceramic turbine for the application is unproven. This task addresses the second option. If the turbine work is held constant, a reduction in turbine temperature is directly proportional to the efficiency increase. The current total-to-static efficiency of the RLV fuel turbine is 58%, leaving a large opportunity for improvement. An increase of 8 points in turbine efficiency would result in an approximate reduction of 275° R (with an approximate inlet temperature of 1825° R) and the possibility of an uncooled metal turbine. Cooler temperatures also increase margins for the metal housings. Alternatively, if the ceramic turbine technology is successful, increased efficiency can be used to reduce the mass flow rate. The mass flow rate through the turbine is currently 64.4 lbm/sec. For every 4 lbm/sec reduction in mass flow rate, engine I_{sp} is increased by 1 sec. If efficiency is increased by 8 points, mass flow rate can be reduced by approximately 10 percent, or 6 lbm/sec, and engine I_{sp} is increased by approximately 1.5 seconds. As a secondary benefit, reducing turbine mass flow rate improves the mixture ratio of the modular thruster, thereby increasing engine I_{sp}. One second of I_{sp} is equivalent to 1500 lbm of payload or 168,00 lbm of gross lift-off weight.

Objectives

The objective of this task is to redesign the hot gas path of the RLV fuel turbine using advanced CFD and optimization techniques with the goal of improving aerodynamic efficiency by 8 points. The efficiency gain would then be used to reduce turbine inlet temperature or to reduce turbine mass flow rate to obtain a higher engine I_{sp}. The final design will be tested and verified in air.

Technical Approach

The technical approach is to team experts in turbine aerodynamic design, analysis, and testing from MSFC, industry, and academia to focus on a more efficient RLV fuel turbine. This approach has been successfully demonstrated by the MSFC Turbine Technology Team for the STME fuel and LOX turbines resulting in a 10 point gain in fuel turbine efficiency and a stage reduction for the LOX turbine. Advanced, innovative analytical tools will be applied to the RLV fuel turbine requirements to generate a highly efficient turbine aerodynamic configuration. State-of-the-art CFD codes and new optimization techniques will be used to perform design parametric studies. Applying these analytical techniques to the aerodynamic design will allow the consideration of many more design concepts than can be considered in a traditional design practice. The team will iterate with Rocketdyne system balance personnel to determine the impact of the turbine design on the engine system. Aerodynamic design details along with analytical and test results will be documented.

Metrics and Potential Off Ramps

There will be two metrics for this task. (1) Nine months after task initiation, an assessment will be made of anticipated efficiency improvement after initial concept development and before analysis and optimization . If the anticipated performance improvement is not at least 1 point higher than the baseline, a decision will be made as to whether to proceed with analysis and optimization. (2) At the end of the first quarter of FY00, an assessment will be made of the predicted efficiency improvement after detailed analysis and optimization. If the predicted efficiency improvement is not at least 1 point higher than the baseline, a decision will be made as to whether to proceed with testing.

Benefits

The benefits of this task for the RLV program are the design options that are made available through improved turbine performance: (1) Turbine temperatures can be reduced possibly allowing a uncooled metallic blisk, (2) Mass flow rate through the turbine can be reduced, thereby increasing Isp, or (3) a combination of temperature reduction to provide additional margin for the metallic housings and a reduction of mass flow rate through the turbine to increase I_{sp} can be chosen. The development and demonstration of analytical techniques for turbine aerodynamic design will benefit the RLV program as well as turbopump development for any reusable or expendable launch vehicle.

Scope of Work/Approach

Baseline Analysis

Rocketdyne will supply the geometry definition of the baseline RLV fuel turbine to MSFC . Inlet and exit flow boundary information such as inlet total pressure, inlet total temperature, inlet density, total to static pressure ratio, inlet Mach number, inlet flow angles, and Reynolds number will also be provided to MSFC from Rocketdyne. MSFC will perform 3D unsteady CFD analysis of the baseline design and provide a turbine environment definition and predicted efficiency to the team. Virginia Commonwealth University will support MSFC in this analysis by assisting in the set up of the grid generation and input files, trouble-shooting and correcting problems that may arise during analysis, and assisting in post-processing.

Code Development and Enhancement

Virginia Commonwealth University will enhance the unsteady CFD code, CORSAIR, to reduce run times, to enable more rapid grid generation, and to simplify post-processing. They will also develop an interface between CORSAIR and optimization software supplied by the University of Florida. The University of Florida will develop and evaluate optimization software for turbine design. They will support the installation of the software on an MSFC computer. They will develop a procedure for applying the optimization software to turbine design. They will support MSFC with the design parametrics through aiding MSFC in the application of the software, and trouble shooting and correcting problems that may arise in the optimization. Riverbend Design Services will develop design-type software with which to run very rapid analysis. The software will interface with the optimization software to point MSFC in the correct direction for optimal design before running more time intensive CFD analysis. Riverbend Design Services will support the installation of the software on a computer at MSFC and will provide written instructions on the use of the software. They will aid MSFC in applying the software to the parametric designs and trouble shooting and correcting problems that may arise in the application of the software.

Trade Studies

MSFC, Rocketdyne, and Riverbend Design Services will review the current RLV engine layout and system constraints. They will analyze the results of the baseline CFD analysis to determine areas of largest potential improvement. Candidate concepts for efficiency higher than the baseline and within system constraints will be generated by Rocketdyne and Riverbend Design Services. During the design parametrics, they will refine, delete, or add concepts based on analytical results.

Design Parametrics

Design parametrics will be performed for the candidate concepts developed during the trade studies. Rocketdyne will generate all aerodynamic designs for the candidate concepts to be analyzed and optimized. They will provide MSFC with the geometries of the hot gas paths in an agreed upon format. Riverbend Design Services will consult with Rocketdyne to assist in assuring that the intent of the candidate concept is met within the aerodynamic design. MSFC will perform the analysis of the candidate concepts. They will perform rapid design analysis to interface with optimization software. When the field is localized on a design optimum, MSFC will perform parametric, higher fidelity CFD analysis, interfacing with optimization software to produce an optimum design. MSFC will post-process and provide the results to Rocketdyne and Riverbend Design Services in an agreed upon format. Rocketdyne and Riverbend Design Services will analyze and evaluate the results of the design parametrics and suggest concept refinements, if necessary. Rocketdyne will input the results of the design parametrics into their power balance model and perform engine balance analysis. Rocketdyne will report the results of the turbine design impacts to the engine system to MSFC .

Final Design

Based on the results of the analysis, MSFC , Rocketdyne, and Riverbend Design Services will choose a final aerodynamic design that most improves performance while staying within system constraints. Rocketdyne will generate the detailed aerodynamic design of the final concept. They will provide MSFC with geometry information in an agreed upon format to enable CFD analysis. They will also provide MSFC with the details of the flow path and all aerodynamic performance critical requirements such as surface roughness, attachment preferences, platform seal preferences, etc., to enable the mechanical design of the test rig. This information will be delivered in an agreed upon format. MSFC will perform detailed 3D unsteady CFD analysis of the final design and provide the team with a predicted aerodynamic environment and predicted efficiency. Virginia Commonwealth University will support MSFC in this analysis by assisting in the set up of the grid generation and input files, trouble-shooting and correcting problems that may arise during analysis, and assisting in post-processing. Rocketdyne will input the results of the final design and analysis into their power balance model and perform engine balance analysis. Rocketdyne will report the results of the turbine design impacts to the engine system to MSFC .

Test and Evaluation

A test article of the final aerodynamic configuration will be designed, manufactured, built, highly instrumented, and tested in air in MSFC's Turbine Test Equipment. The turbine design will be evaluated based on test and analytical results. CFD and optimization software will be verified with test data.

Rig Design and Fabrication: MSFC will perform the mechanical design for the turbine test rig. The test article will be scaled to fit within the current test equipment and to take advantage of as much existing hardware as practical. The outer casings, core module (shaft, bearings, seals, etc.), exhaust duct, rotating rings, and slip ring unit from an existing test article will be available. MSFC will provide all facility and existing hardware information required by MSFC . MSFC will perform project management for the design and fabrication of the test rig. They will ensure all requirements for testing in the TTE (mechanical design, factors of safety, pressure and spin tests, etc.) as specified in the requirements document to be supplied by MSFC are met, and that manufacture meets drawing requirements within specified tolerances. They will also ensure that the rig will fit in the test facility. MSFC will perform all necessary stress calculations for the test.

Rig Build and Facility Information: MSFC will assemble the rig according to the assembly drawings within specified tolerances. They will install the rig into the facility. MSFC will ensure that the facility and test article are ready for test.

Test: MSFC will plan the test, develop the test matrix, and evaluate instrumentation requirements. Rocketdyne and Riverbend Design Services will assist in the development of the test matrix and will evaluate what measurements are required to meet test objectives. MSFC will test the turbine according to the test matrix.

Data Analysis: MSFC will analyze the data and provide overall performance parameters to the team. They will compare test data to pretest predictions. They will ensure that test objectives have been met.

Design Evaluation: MSFC , Rocketdyne, and Riverbend Design Services will examine the analytical and test results to evaluate overall turbine performance and to determine if program objectives have been met.

Analysis Benchmarking: MSFC , Virginia Commonwealth University, and the University of Florida will verify analytical predictions with the test data. Discrepancies will be identified and explained.

Task Management

A CDT has been formed to perform the work in the Turbine Performance Optimization task. The Turbine Performance Optimization CDT is chartered to develop/enhance and validate analytical tools, to apply these tools to the RLV fuel turbine, and to improve the efficiency of high-performance turbines. This team will consist of members from MSFC Rocketdyne, Riverbend Design Services, Virginia Commonwealth University, and the University of Florida. Key personnel and their responsibilities are described in the following sections. As a minimum, in addition to the PI, the following disciplines will be members of the Turbine Performance Optimization CDT:

turbine aerodynamic design
analytical code development
analytical code application
turbine performance testing
mechanical design
stress analysis

The PI will coordinate all activities, write status reports required by the project manager, make status presentations as required by the project manager, and manage the task budget and schedule.

Documentation and Reporting

The PI will provide all reports as required by the Project Manager. Turbine aerodynamic design details along with analysis and test results will be documented by the PI. All team members will support status meetings at MSFC two times a year. The PI will support project reviews as required by the project manager.

Deliverables

In addition to the intermediate and final reports that will document this activity, this task will provide a verified, detailed turbine aerodynamic design with quantified benefits to the RLV engine system. Furthermore, advanced analytical tools developed or enhanced and verified in this task will be available for application to future turbopump programs.

Schedule and Budget

Activity Name	**FY98**		**FY99**				**FY00**				**Total**
Task Milestones and Off Ramps	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	
Baseline Analysis Completed			▲								
Go/No Go Proceed to Analysis					▲						
Complete Parametric Design							▲				
Go/No Go Proceed to Testing							▲				

Test Completed										▲	
Reviews											
1. Task Status Review				▲		▲		▲		▲	
2. Team Meetings/Test Reviews			▲		▲		▲		▲		
Task Elements											
1. Baseline Analysis (FTE/$)											**0.21/ 45.8K**
MSFC FTE		0.21									0.21
MSFC Equipment		34.8K									34.8K
RKDN		10.0K									10.0K
VCU		1.0K									1.0K
2. Code Development and Enhancement (FTE/$)											**0.00/ 127.0K**
VCU		11.0K	16.0K								27.0K
Univ. of Florida		12.0K	40.0K								52.0K
River Bend Designs		13.0K	35.0K								48.0K
3. Trade Studies (FTE/$)											**0.08/ 34.9K**
MSFC FTE			0.08								0.08
RKDN		1.5 K	18.0K								19.5K
River Bend Design			15.4K								15.4
4. Design Parametrics											**0.50/ 83.0K**
MSFC FTE			0.5								0.5
RKDN			54.8K								54.8K
River Bend Design			28.2K								**28.2**
5. Final Design											**0.32/ 55.2K**
MSFC FTE						0.16	0.16				0.32
MSFC Equipment							34.5K				35.0K
RKDN					9.0K		7.2K				16.2K
VCU						2.0K	2.0K				4.0K
6. Rig Design and Fab.											**1.73/ 389.2K**
MSFC FTE					0.32	0.76	0.65				1.73
Rig Hardware/Design Support (RECOM)						64.2K	325K				389.2K
7. Rig Build and Installation											**0.24/ 15.0K**
MSFC FTE								0.24			0.24
Build Support (RECOM)								15.0K			15.0K

8. Test											**1.48/ 38.6K**
MSFC FTE						0.24	1.24				1.48
Test Support (EG&G)							25K				25.0K
RKDN							7.2.K				7.2K
River Bend Designs							6.4K				6.4K
9. Data Analysis											**0.16/0.0K**
MSFC FTE									0.16		0.16
10. Design Evaluation											**0.08/ 20.9K**
MSFC FTE										0.08	0.08
RKDN									11.3K		11.3K
River Bend Designs									9.6 K		9.6K
11. Benchmarking											**0.08/ 10.0K**
MSFC FTE									0.08		0.08
VCU									5.0K		5.0K
Univ. of Florida									5.0K		5.0K
12. Documentation											**0.16/0.0K**
MSFC FTE			0.08				0.08				0.16
13. Reviews/Reporting											**0.16/ 36.0K**
MSFC FTE			0.08				0.08				0.16
RKDN			6.0K				6.0K				12.0K
VCU			3.0K				3.0K				6.0K
Univ. of Florida			3.0K				3.0K				6.0K
River Bend Designs			6.0K				6.0K				12.0K
14. Task Management											**0.21/0.0K**
MSFC FTE		0.05	0.08				0.08				0.21

Budget

Year by Year Totals				

MSFC (FTE)	0.26	2.30	2.85	**5.41**
MSFC FTE Costs	4.7K	41.4K	51.3K	**97.4K**
MSFC Equipment	34.8K	0.0K	35.0K	**69.8K**
Rig Sub and Material	0.0K	64.2K	365.0K	**429.3K**
RKDN	11.5K	87.8K	31.7K	**131.0K**
VCU	12.0K	21.0K	10.0K	**43.0K**
Univ. Of Florida	12.0K	43.0K	8.0K	**63.0K**
Riverbend Design	13.0K	84.6K	22.0K	**119.6K**
Total Cost	88.0K	342.0K	523.0K	**953.0K**

Appendix 16 Metal Matrix Composite Components - Turbo Demo

Objective

The objective of this task is to demonstrate and validate the utilization of an advanced material in the fabrication of high-pressure structural housings that will provide significant engine weight decrease. The Revolutionary Reusable Turbopump Technology (RRTT) demonstrator is a high-pressure, oxygen rich turbine driven pump. This task will use this pump to demonstrate the integration of Metal Matrix Composites into the system by replacing two of the major castings of the RRTT with alternate components fabricated from Cu-based MMCs. While the Cu-based MMC is required for the oxygen rich environment of RRTT, Al-based MMCs will also be addressed at a reduced level to provide the designer with the option of using the Al-based components for an even greater reduction in engine weight where appropriate.

Technical Approach

The technical challenge is to design and fabricate reinforcing fiber architectures in a metal matrix composite that maximizes weight savings in complex shaped, highly loaded structures.

A continuous fiber reinforced MMC will be used to replace the existing turbine and pump inlet housings on the RRTT to demonstrate the weight reduction benefits. MMC was selected for both the hot GOX and cryogenic LOX housings after considering competing lightweight materials, such as silicon nitride, polymer matrix composites, and ceramic matrix composites. The main descriminators in favor of MMC are the recent industrial demonstrations of large, complex MMC hardware, the availability of manufacturing facilities capable of fabricating RLV scale housings, and the inherent ox-rich environmental capability for long0duration use without coatings or claddings. Despite these recent advances, the current TRL for MMC TPA housings is only three. This task will bring the TRL for MMC to the required level.

An innovative process involving pressure infiltrated cast MMC has been selected as the process of choice for this task. The leading candidate MMC is a copper-based alloy reinforced by Nextel 610 continuous alumina fibers. After the candidate alloy and fibers are selected based on key screening criteria such as ox-compatibility, specific strength and producibility. Additional testing will be performed to assess H2 compatibility to enable a wider range of future applications. With the selected MMC, scale-up of the processing technique for large-scale TPA housings will be demonstrated, leading to proof testing of representative components. Housings will then be fabricated and tested for subsequent assembly in the RRTT. Also, in parallel, a new ox-rich gas generator will be designed and fabricated by Rocketdyne and tested to allow hot-fire testing of the RRTT with the new lightweight housings installed.

Approach

Material Selection.

Candidate alloy chemistries shall be identified and preferred candidates selected for the matrices to be used with Nextel 610 continuous fibers in each of the RRTT LOX turbopump demonstration components (turbine housing an pump inlet housing). Primary candidates are copper-based alloys for the turbine housing and aluminum-based alloys for the pump inlet housing. Final selection of the material shall be made utilizing the data collected in 22000 and 23000.

Oxygen Compatibility & Exposure Testing.

Ignition testing (particle impact ad rubbing) in box LOX and GOX (as appropriate) shall be performed with the preferred candidate MMC materials in oxygen pressures 50% higher than he RRTT LOX turbopump operating conditions. Oxidation exposure testing shall also be performed for the turbine housing material. MMC coupons shall be fabricated for these tests. NASA-MSFC shall assist Rocketdyne in defining a detailed environmental compatibility test plan for the preferred candidate MMC alloys. NASA-MSFC shall perform the actual test plan and assist Rocketdyne in analysis of the results.

Mechanical Physical Property Testing

A coupon testing program for critical mechanical an physical properties shall be performed to support materials selection for the two housing applications. MMC coupons shall be fabricated for these tests. NASA-MSFC shall assist Rocketdyne in defining a detailed mechanical and physical property test plan for the preferred candidate MMC alloys. NASA-MSFC shall perform the actual test plan and assist Rocketdyne in analysis of the results.

Pump and Component Detailed Design

Rocketdyne shall utilize lessons learned in tasks 24000 and 25000 and produce a detailed design of pump inlet and turbine housings. Detail designs of existing RRTT pump hardware needed to accommodate new light weight components shall also be supplied.

Fabrication

Rocketdyne shall determine a viable fabrication process and procedure which produces a full scale MMC turbopump inlet and turbine housing suitable for assembly in a RRTT LOX pump. NASA-

MSFC shall assist Rocketdyne (and MMCC and Foster-Miller) in defining an overall processing scheme for fabrication of the MMC housing. Housing will be proof pressure tested.

Misc Part Procurement

Miscellaneous hardware (nuts, bolts, seals, etc) shall be procured to support a new LWTP configuration.

Turbopump Assembly and Disassembly Procedures

Generate a disassembly procedure for the existing RRTT turbopump and an assembly/disassembly procedure for the new LWTP. The procedures will be written with input from Rotating Machinery Analysis and EDL.

Tool Design and Fabrication

Design and fabricate tooling to support the assembly/disassembly procudures generated in task 33000.

Disassembly

Disassemble the existing RRTT turbopump with tooling fabricated in task 33000 to a degree which supports incorporation of new LWTP hardware per established disassembly procedures.

Recurring Fabrication

Fabricate redesigned turbopump hardware needed to accommodate new off-design requirements and light weight components for LWTP (new inducer, new bearing, etc).

Pump Assembly with New Components

Assembly the new LWTP with new components per the LWTP assembly procedure.

Procurement

Procure wrought material to support fabrication of combustor, injectors, flanges and inlets. Procure ignition source and required instrumentation from outside vendors.

Ox Rich Preburner Design

Design and analyze components necessary to support a viable ox rich preburner assembly. Produce and release detail and assembly drawings. Release drawings into Rocketdyne metaphase system.

Fab, Check-out and Assembly

Fabricate and assemble components per released engineering drawings. Design and fabricate necessary assembly tooling. Conduct preburner cold flow tests.

Facility Preparation

Design and fabricate facility hardware (flanges, spools, etc) necessary to support preburner hot fire test. Generate hot fire test plan.

Preburner Hot Fire Test

Conduct preburner hot fire tests plan. Conduct post inspection and data analysis efforts.

Facility Preparation & Support Interface

Design, fabricate and install necessary components to support hot fire test of LWTP. Generate an interface control document and hot fire test procedures.

Test Ops Readiness Review

Conduct a test operations readiness review with all parties pertinent to the support of the LWTP hot fire test.

Test Activation Support Interface

Conduct activities necessary to support test activation support interface.

Test Planning

Generate a test plan to support the LWTP hot fire test.

Power Pack Install and C/O

Integrate test article onto test stand along with necessary support equipment. Conduct necessary safety checks as required.

Power Pack Hot Fire Test

Conduct hot fire test of LWTP per prescribed test plan. Moniter, analyze and collect data as planned. Moniter system safety as required.

Data Analysis

Analyze data collected during hot test. Publish data and analysis as well post test conclusions.

Post Test Inspection

Disassemble LWTP and inspect hardware. Note hardware conditions and publish findings.

Management Approach

Rocketdyne Program Management shall manage and administer the NASA NRA Light Weight T/P (LWTP) task as well as the customer-program interface. A systems engineering approach will be used to ensure technical progress meets program goals. Rocketdyne shall provide business planning and financial management of resources during the course of the program. Rocketdyne shall track and manage the program schedule. A master schedule covering the contract shall be developed and updated with intermediate milestones, timeliness and relationships for tracking program progress. Rocketdyne shall furnish a Contract Administrator to be responsible for definitizing the contract making any necessary contract changes. Pricing will adjust the contract value according to any contract changes.

Task Management

Project engineering shall manage the technical effort on the NASA NRA LWTP task. This includes providing technical guidance to all team members. An Integrated Product Team (IPD) engineering approach will be used to track and ensure technical progress meets program goals.

Reporting

Data management shall manage all required data documents. Data reporting shall be mutually agreed upon between Rocketdyne and NASA. The following reports as a minimum shall be supplied: 1)

Informal Weekly Technical Status Reports. 2) Monthly status letter beginning July 01, 1998, and 3) A final report due 30 days after completion of the technical effort.

Process/Product Plan of Action (PPPOA)

The PPPOA will provide clear process path for the LWTP. Program Management shall be responsible for defining program criteria, assumptions, ground rules and level of analysis. Efforts also include establishing level of customer, supplier, and in-house team participation. Project and Materials engineering shall provide technical input as well as establishment of new analytical tools. Design engineering shall determine scope of design process.

Appendix 17 650 KLBF LO2/LH2 Engine Demonstration

In the last twenty five (25) years, only three 1-02/1-1-12 large booster engines have been developed by the free economy nations. All of these designs were driven by performance rather than cost or schedule. To achieve the high performance goals, pushing the limits of technology resulting in expensive technology and manufacturing development. The resulting engine designs were both complex and extremely costly to manufacture. While continuous efforts have been underway in the United States to reduce existing engine costs through redesign of key components, these effort have yet not resulted in any significant reduction in overall engine cost.

TRW and NASA are performing this two phase task under a Cooperative Agreement. TRW will demonstrate an Ultra Low Cost Engine (ULCE) operating at 650,00 LIBF thrust. This engine will include GH2 powered Turbopumps, Propellant Valves, Injector Assembly, and an Ablative Combustion Chamber Assembly. The testing of this engine will fully demonstrate the capability of a pintle injector, ablative lined engine to achieve high performance and combustion stability while burning L02A_H2 propellants at 700 psia chamber pressure. TRW proposes to use the engine that was completed in 1996 using TRW, Allied Signal Aerospace, and McDonnell Douglas Aerospace funds. TRW plans to use existing materials and engine parts to prepare a second combustion chamber and nozzle assembly with film cooling. The TRW engine will be ready to mount on the NASA SSC test stand with the addition of interface plumbing and a thrust structure that are compatible with both the SSC E-1 test stand and the TRW engine. Included in this revised proposal are the TRW costs and the value of the Pump Fed Engine Assembly.

The initial ULCE Design, Manufacture, and Component Test activities that would lead to a complete demonstration of the ULCE have been completed. The next stage is the proposed Pump Fed Engine Test activity under a Cooperative Agreement with NASA. The final demonstration testing of a flight type engine with gas generator powered turbopumps will be the subject of future contract activity.

PROJECT DESCRIPTION

The objective of this program is to demonstrate an ultra low cost engine that will substantially lower the cost of launch vehicles in the U.S.A. and will enhance America's competitiveness in the international space transportation market. This program shall conform to Section D of NASA's 14 CFR Part 1272 "Cooperative Agreements with Commercial Firms." TRW is to supply its 650,000 lbf sea level L02/LH2 engine (less a gas generator) to this program for test by NASA SSC on the E-1 test stand. The engine includes the TCA, propellant turbopumps (to be driven with GI-12), powerhead ducting and test stand interface structure/ducting. There are also spare parts and materials to assemble a second combustion chamber assembly for test. NASA will supply all propellants and test services associated with testing.

The key milestones for the pump fed test program are:

	Months ATP
• Complete TTB Interface Hardware	6.0
• Install Powerhead Assembly on Test Stand and Cold Flow	8.0
• Complete Engine #1 Test Series (#E1 and #E3)	12.0
• Complete Engine #2 Test Series (#E2)	13.5

The goals of the three hot fire test series are:

#E1 Scale up data (performance, life and stability) in short duration tests of the engine with an all rubber ablative system.

#E2 Performance, stability and short duration life data on TCA that has film cooling and a silica phenolic throat.

#E3 Stability damping characteristics at full and throttled thrust operating levels after a bomb detonation pressure pulse.

MANAGEMENT APPROACH

NASA MSFC/SSC test organizations have years of experience in the testing of a wide variety of rocket engines, TRW will follow their lead in the distribution of responsibilities and coordination of the test effort. NASA established procedures that cover the testing of rocket engines from receipt of hardware to final data distribution will be used for this program. It is expected that all safety requirements and issues will be NASA's responsibility with overall safety being a shared responsibility.

TRW will be responsible for all hardware modifications and change out. The hardware work accomplished while the engine is on the thrust stand will be in accordance with current MSFC procedures and restrictions for contractor personnel on the test stand.

The test plan was prepared by TRW with SSC's test people's inputs. Test procedures were prepared by NASA personnel and reviewed by the TRW test engineer. All deviations to the test plan/procedures that relate to the engine testing require concurrence by both the NSA test conductor and TRW test engineer before implementation. A desired instrumentation list will be provided by TRW as part of the test plan. NASA will be responsible for the facility instrumentation and TRW will be responsible for the instrumentation on the engine. Thermocouple installation and location is a joint responsibility.

The last tests of test series #1 will consist of three bomb tests. TRW will prepare the bombs and install them on the engine. It is TRW's understanding that prior Rocketdyne testing at MSFC was limited to bombs of less than 15 grains. TRW is proposing up to 90 grain bombs for the stability testing to be consistent with CPIA 655 requirements. If there is a SSC limit on bomb size, TRW will reduce the bomb sizes to be consistent with any established NASA procedures.

As the program is currently planned, TRW will supply to MSFC during the test periods: - Engine #1 ready for test – Engine interface ducting and thrust interface structure - Combustion chamber assembly #2 ready for test - Additional hardware and spare parts - Two test engineers and two senior technicians

It is anticipated that during the test periods NASA will supply:
- Test Stand E-1ready for engine testing
- All propellants and consumables during the tests
- Test crew
- Standard facility services
- Data acquisition and reduction to engineering parameters

The tasks elements to be conducted by TRW shall be as follows:

Task I Design and Analysis
TRW shall design interface propellant ducting and test stand structures required for integration of the powerhead with the current TTB facility configuration. The film cooling injector designs will be completed and new design for TEA igniters will be prepared. Design and analysis support to the NASA – SSC test facility E-1 will be accomplished under this task.

Task 2 Manufacture New and Modified Hardware
TRW shall manufacture the new hardware planned for installation of the engine on the test stand, modified injector hardware, and film cooling hardware. Design modifications to the existing engine shall be conducted as needed. The major hardware elements to be manufactured in this task are:

- Powerhead/facility interface hardware (propellant ducting and stand interface structure)

- CCA #2 ablative materials and installation
- Film cooling injectors and manifold

Spare injector and chamber hardware
Miscellaneous test support materials

Task 3 Engineering and Support

TRW shall provide management, engineering, and analysis support for all program tasks. During the installation and testing at SSC, TRW shall provide both engineering and technical support. Engine adjustments and hardware modifications shall be the responsibility of the supporting TRW engineers and technicians.

Task 4 ASA Subcontract

TRW shall contract with ASA to provide turbopump integration, acceptance testing and MSFC/SSC test stand engineering and technical support for the cold flow and hot firing tests.

Task 5 Power Head Cold Flow Tests

TRW shall provide an overall test plan and coordinate with the NASA test conductor on the detailed procedures for power head assembly installation and cold flow testing. The power head shall be integrated at TRW and shipped to SSC for testing. The power head will be mounted on SSC test stand E-1 and special injector ducting to facilitate cold flow testing will be installed. The L02 side will be flowed to test its integrity and calibrate the L02 system with respect to time lines and flow rates. The same process will be repeated with the LH2 propellant flow circuit. As an option the TRW dual propellant flow fixture can be installed and both sides flowed at the same time.

Task 6 Engine #1 Integration

TRW shall complete final torqueing of interface flanges and install the TEA injector system on the chamber head-end. The engine shall be shipped to NASA for integration on the powerhead assembly used for cold flow tests. Igniter checkout tests will be conducted with the combustion chamber installed on the powerhead assembly.

Task 7 Engine #1 Testing

TRW shall use the Task 6 rubber ablative lined combustion chamber assembly and power head assembly for a series of facility check-out firings. After completion of successful facility checkout tests, pump fed engine performance tests will be conducted. During the performance testing, short duration life data will be obtained. Separate life tests will be conducted at high perfon-nance injector settings. A series of three bomb tgsts will be conducted to demonstrate the engines' combustion stability (these bomb tests may be delayed until after Engine #2's life tests if desired by the test conductor).

Task 8 Engine #2 Integration

TRW shall integrate the film cooling and a silica phenolic throat into a second combustion chamber assembly. Ablative liners shall be installed and chamber joints will be filled with ablative. TRW shall conduct pressure and leak tests at the appropriate integration points. The ablative will be inspected using a Shearography technique. After completion of the first series of testing, TRW shall remove, with NASA's assistance, the fired combustion chamber and install the new combustion chamber with a hard throat and head end film cooling. The injector shall also be removed and a new fuel manifold installed to supply the film cooling to the chamber. All the new plumbing shall be installed by TRW with NASA's support.

Task 9 Engine #2 Testing

Film cooling performance tests shall be performed to measure the engine performance with various amounts of fuel film cooling. Short duration ablative life data shall be conducted in conjunction with the performance tests. Ablative life tests will be conducted on the engine with the injector and film cooling set for the optimum conditions. After completion of the testing, TRW shall assist MSFC in removing the engine from the test stand. The powerhead assembly and combustion chambers will be returned to TRW for post morterm evaluation.

Task 10 Post Test Engineering

TRW will analyze the engine test data and use the engine model to define the optimum design characteristics of the pintle engine design. The ablative hardware will be sectioned and analyzed to determine its life characteristics.

Task 11 Documentation

TRW shall prepare and submit to NASA the following documentation:

Item	Delivery
Technical Status	Monthly
Milestone Status and Invoice	Monthly
Test Series #1 Preliminary Report	One month after completion of tests
Final Report	One month after hardware returned to TRW

Task Objectives

The overall objective of this task is to develop an ultra low cost, environmentally clean booster engine family that can provide the first stage impulse to all U.S. launch vehicles at an engine cost of less than $511 LBF. In addition to use on the launch vehicle booster stage, this engine is a strong candidate for emerging applications such as flyback booster, heavy lifter for outer space missions, liquid propellant booster replacements for SRB's and all reusable booster applications. These ultra low cost engines will bum cryogenic 02 with either cyrogenic H2 or RPI at relatively low combustion pressures (300 psia to 1400 psia). The engine configurations are to be designed around the coaxial pintle injector, single stage foil bearing turbopumps, and fuel film cooled ablatives, and ablatives with hard throats.
The objective of this proposed project is to take the first step in the process of developing ultra low cost engines by demonstrating performance, stability and life using an existing TRW 650,000 LBF, L02/LH2 ablative thrust chamber assembly and GH2 powered propellant turbopumps. The proposed test series will be conducted on NASA MSFC test stand TTB in a pump fed configuration. The test results will demonstrate if this engine is ready to continue on to full engine testing with gas generator powered turbopumps or whether additional research must be conducted on the injector concept or ablative system. These tests will give NASA good decision points as to whether to support or disregard pintle injectors as low cost candidates for booster size engines.

In the early days of Space Shuttle planning, the booster propulsion options included SRMs, pump fed, L02/RP- I propellant engines and simple, pressure fed, earth storable, propellant engines. Since the Space Shuttle developments of the SSME and SRM's there have been no new full scale American engine developments. In addition, the world's aerospace community has moved away from earth storable propellants for boosters to L02/LH2 and L02/RP- I propellants to avoid the potential safety hazard related to large oxidizer spills on the ground as well as in the early launch phase. In addition this engine system answers the need for a major reduction in vehicle costs in order that the U.S. be competitive in providing international launch service at an acceptable price.

Coupled with the enormous pressures for cost reduction and safe/ reliable/ environmentally clean launch operations, there has been a strong push for very low cost booster rocket engines burning cryogenic 02 oxidizer with either cryogenic H2 or hydrocarbon fuels. In the booster phase of the spacecraft transport, all technology roads must lead to minimum cost. Higher reliability and safety relate directly to lower insurance costs. Additionally, boost stage performance can be decreased and weight can be increased in order to significantly reduce overall costs. The cost of the booster engine is also related to cycle/hardware complexity and combustion pressure. An example of this relationship is presented in Figure 3 where engine cost USD (U.S. dollars)/LBF of engine thrust is related to chamber pressure. Existing L02/LH2 engines and the RS-27 are compared to much simpler cycle and lower pressure next generation engines. With these next generation engines, where low cost was the only goal, the engine cost reductions are from one to two orders of magnitude from the existing engines. The ENM costs are 1/3 to 1/10 of that spent for the existing engines.

Power Head Cold Flow Tests

TRW will provide the injector assembly fabricated as part of an earlier TRW program for integration into the power head assembly. The GH2 powered turbopump assemblies will be integrated and subjected to acceptance tests at ASA. These TPAs along with the propellant ducting and propellant shut-off valves will be installed on the injector to form the power head assembly. Propellant ducting designed to transition from the existing TRW propellant inlets to the test stand TTB propellant outlets will be installed on the power head assembly. Test stand interface structures will be mounted on the power head assembly prior to shipment to MSFC TTB.

After assembly and checkout at TRW, the power head assembly will be shipped to NASA's SSC test facility. The power head assembly will be installed on SSC’s E-1 test stand and tested as a separate assembly using L02/LH2 propellants. Cold flow testing of the injector assembly will be performed first with the L02 propellants and then with the LH2 propellants. TRW can furnish an adapter for the injector which separates the propellant flows for this test if there is a need to perform both cold flows simultaneously or to duct H2 to a flare stack. Approximately 110 seconds of run time will be accumulated in 18 cold flow tests. The objective of these tests is to demonstrate the safe operating conditions of the engine integrated on the NASA test stand, determine valve and flow timing and to calibrate the overall engine/facility propellant flow systems.

Engine Testing

The tests to be performed on engine #2 are defined in section 1.5. These tests consist of two series: film cooling performance tests and long duration ablative life tests. Both of these tests series will use injector configurations optimized in Task 7 with any modifications as indicated necessary by the film cooling tests.

After completion of the Task 9 firing tests, the complete engine will be returned to TRW for post test analysis.

At the completion of the engine hot fire testing, the following engine components will have been tested:

Structure	Not flight type (designed to mount to MSFC thrust ring)
Plumbing	TS-TTB interface ducting and TRW TCA ducting with high safety factors
Propellant Valves	Flight valve with heavy weight housings
Injector Assembly	Flight configuration with high safety factors for initial test stand operation

Post Test Engineering

A hardware postmortem will be conducted on the ablative systems to determine erosion characteristics, surface conditions, chemical reaction and structural integrity. The data provided by the engine tests and the engine model analysis will be evaluated to determine final performance of the engine and to predict the performance characteristics of the engine when the gas generator and warm gas turbines are added. Any data requested by NASA to make a decision about continuing on to Phase II engine testing will be prepared as part of this task. The final report will be prepared in this task and delivered to NASA.

Documentation

Documentation to be delivered to NASA during this program are:

a. Monthly status reports.
b. Milestone status and invoices per milestone payment schedule.
c. Test Series #1 preliminary report.
d. Final report.

Responsibilities

TRW has extensive experience in similar development programs using similar organization and matrix management. Under this system, the overall program management would be in the Propulsion and Combustion Center. Kathy Gavitt serves as Program Manager for this effort and directs the TRW test team at MSFC/SSC and serves as the princilg point of contact at TRW for the SSC test director. Tom Mueller heads up the system engineering and performance modeling efforts. Frank Stoddard, who managed the 16.5 KLBF and the 40 KLBF programs serves as a technical consultant throughout the program. John Weede who served as the Program manager during the 12 month build of the 650 KLBF ULCE hardware also supports the proposed effort. Harry Thom, who was responsible for manufacturing support of the

650 KLBF ULCE hardware fulfills the same role in this program. Similarly, Chris Murphy, who was responsible for ablative installation and TCA integration on the 650 KLBF LTLCE hardware performs in a similar capacity on this program.

Appendix 18 Integrated Powerhead Demonstration

Scope of Work

This statement of work defines the effort required to identify, develop, and demonstrate the technologies for highly reliable, long-life, cryogenic (liquid hydrogen/liquid oxygen) powerheads. The term powerhead as used in this statement of work refers to rocket engine turbopumps and the preburners that provide hot drive fluids to the turbopump turbines. A preliminary engine design will be developed to define interface and performance requirements for the turbopumps and preburners. The preliminary engine design task will also allocate reliability, operability, supportability, and maintainability requirements. Turbopumps and preburners will then be designed and fabricated to meet these requirements. The technology will be demonstrated in component and integrated testing at the Phillips Laboratory Propulsion Directorate, Edwards AFB, CA.

Background

Propulsion systems on current U. S. spacelift systems achieve high reliability only after extensive pre-flight inspections and tests. These propulsion systems require significant ground and inflight support that increases not only the cost of support equipment, but the operational costs due to maintenance and inspection of the support equipment. Launch system operational effectiveness is hampered by propulsion system high sensitivity to contamination and environmental conditions such as humidity and plume recirculation. As a result, costs are high and launch responsiveness cannot be achieved.

Reliability and life can be increased by incorporating new materials and by using alternate power cycles to reduce the severity of engine component environments. Launch vehicle life cycle costs can also be reduced by increasing the reliability of the propulsion system through application of built-in test and health management systems. For both expendable and reusable propulsion systems, operational and equipment costs can be reduced by eliminating propulsion system services that add to ground and vehicle support equipment. The least reliable and life-limiting components of current expendable and reusable hydrogen/oxygen liquid rocket engines are the high-pressure turbopumps. New designs, materials and fabrication techniques have undergone sufficient exploratory development to proceed with advanced component development and demonstration.

The reliability requirements and operational effectiveness needs of expendable propulsion systems become even more difficult to achieve in reusable systems where higher performance levels and long-life are added constraints. For example, on current reusable vehicles post-flight maintenance and refurbishment costs of the propulsion systems approach five percent of the original hardware cost. Since expendable propulsion systems requirements are encompassed by the reusable propulsion requirements, this statement of work defines the effort to develop turbopump and preburner technologies for cryogenic propulsion systems that meet the requirements of reusable launch system concepts. The technology developed will, however, apply to the reliability, operability, and responsiveness needs of expendable systems.

A mixed preburner engine cycle scheme offers some advantages over current hydrogen/oxygen power cycles. Two potential versions of this cycle are shown in Figures 1 and 2. Figure 1 shows a more conventional hydrogen cooled thrust chamber assembly whereas Figure 2 depicts a cycle in which oxygen is used for some of the thrust chamber assembly cooling. These cycle schematics are generic in nature and are not based on control analysis or extensive power balance analysis. Heat exchangers may or may not be required. The preferred thrust chamber assembly cooling circuit routing does not have to be as depicted in these figures, and valving and propellant routing for effective control of the engine may be other than shown in the figures.

APPLICABLE DOCUMENTS

In the event of a conflict between the SOW and the documents herein, the SOW shall take precedence.

Military Standards

Mil-Std-882C	Systems Safety Program Requirements, 19 Jan 93
Mil-Std-1388-1A, Notice 3	Logistics Support Analysis, 28 Mar 91
Mil-Std-1543B	Reliability Program Requirements for Space and Launch Vehicles, 25 Oct 88

Other Documents

DOD Directive 5230.25	Withholding of Unclassified Technical Data From Public Disclosure, 6 Nov 84

Terms and Definitions

Powerhead: The term powerhead as used in this statement of work refers to rocket engine turbopumps and the preburners that provide hot drive fluids to the turbopump turbines.

Life-Cycle Costs: The total cost of an item or system over its full life. It includes the cost of development, acquisition, ownership (including operation, maintenance and support costs), and disposal.

Maintainability: A measure of the time or maintenance resource needed to keep an item operating or restore it to operational status. Maintainability may be expressed as the time to do maintenance (for example, Maintenance Downtime per Mission), as a usage rate of manpower resources (for example, Maintenance Man-Hours per Mission), as the total required manpower (for example, Maintenance Personnel per Operational Unit), or as the time to restore a system to operational status (for example, Mean Downtime).

Operability: The characteristics of a system that make it able to accomplish an operational mission in a direct, timely, and dependable manner in support of national needs.

Reliability: The probability that an item will perform a required function under specified conditions for a specified period of time or at a given point in time. Also expressed as the average time an item will perform a specified function without failure.

Responsiveness: A measure of the degree to which an item is in an operable and commitable state at the start of a mission when the mission is called for at an unknown (random) time.

Supportability: The degree to which system design characteristics and planned logistics resources, including manpower, meet system operational utilization requirements.

REQUIREMENTS

A preliminary project work breakdown structure (PWBS) for the Integrated Powerhead Demonstration is shown in. All turbopump and preburner performance tests and integrated powerhead tests will be conducted at Phillips Laboratory, Edwards AFB. Phillips Laboratory Propulsion Directorate personnel will conduct an integration and configuration control task to assure the preburners, turbopumps, and special test equipment interfaces are compatible with each other and the facility. A suggested contract WBS for a powerhead component is shown in Figure 4.

Technology developed under this effort is subject to the International Traffic and Arms Regulations (ITAR). To protect the critical technology to be developed under this contract all data items shall be marked as follows:

WARNING: This document contains technical data whose export is restricted by the Arms Export Control Act (Title 22, USC, Sec 2751, et seq.) or the Export Administration Act of 1979, as amended, Title 50, USC, App 2401 et seq. Violations of these export laws are subject to severe criminal penalties. Disseminate in accordance with provisions of DOD Directive 5230.25.

Management

Program Management

` The contractor shall develop and implement a management program that clearly defines how the contract will be managed and controlled. A task matrix keyed to the Contract Work Breakdown Structure shall be developed in sufficient detail to identify contractor and subcontractor responsibilities. The contractor shall report progress in a manner that continuously affords the Government visibility into the contractor's progress. The contractor will provide requested news releases iaw the DD 254, Contracting Security Classification, Block 12 to the Government Program Manager for approval through the Government Public Affairs office. (A001/CSSR, A002/CFSR, A003/CWBS, A004/Subcontractor Progress Report, A005/R&D Status Report, A006/Program Plan, A010/Long Lead Items List, A011/Presentation Material, A014/Data Accession List, B003/Final Report)

Systems Engineering

The contractor shall develop a mixed preburner cycle preliminary engine design. This engine cycle has an oxidizer-rich preburner to provide the drive fluids to the oxygen turbopump. The engine thrust level and propulsion requirements shall be developed by applying the IHPRPT goals.to the straw-man vehicle concept presented in the Space Propulsion Division Memorandum "Reusable System Concept for Propulsion System Trade Studies", 25 Feb 94. The contractor shall conduct trade analyses among cost, performance, weight, reliability, life, maintainability, and supportability. The objective of the propulsion system design is to minimize the launch system life-cycle costs while achieving the propulsion system reliability. Consideration shall be given not only to cost factors directly related to the propulsion system but also vehicle and facility cost factors affected by the propulsion system performance and support requirements. In addition to functional requirements, weight, cost, reliability, maintainability, and supportability shall be allocated to engine components. In support of this design effort the contractor shall accomplish from Mil-Std-1543B:

To assess the relative advantages of the engine concepts the contractor shall accomplish Task 203 from Mil-Std-1388-1A, Notice 3, tailored as follows:

Task 203.2.3 Determine the approximate Operational & Support (O&S) costs, logistic support resource requirements, reliability, maintainability, producability, and readiness values of the Baseline Cxxx System (BCS) identified. Identify these values for the preburner and the turbopump level. Values shall be adjusted to account for differences between the BCS profile and the new system/equipment's use profile where appropriate.

(A007/ Design Analysis Report, A008/Reliability Allocation Assessment Report, A009/Design Review Data Package, A011/ Presentation Material, B001/Conceptual Drawings)

A integration task shall be conducted to coordinate the preliminary engine design with the Integrated Powerhead contractors and the Government to obtain an integrated engine design. The contractor shall conduct a design review after completion of the preliminary engine design. The contractor shall obtain written Government Procuring Contracting Officer (PCO) approval of the preliminary engine design before proceeding with detailed component design. The contractor shall develop and deliver to the government within 120 days a scale model of the engine concept following approval of the preliminary engine design. Informal design reviews may be held at times agreed to by the Government and the contractor.(A007/Design Review Data Package, A011/ Presentation Material, B001/Conceptual Drawings)

Oxygen Turbopump

The contractor shall design an oxygen turbopump. The turbopump design shall be sized to a nominal 250 klb engine vacuum thrust level. The turbopump shall be designed to demonstrate the technologies incorporated into the preliminary engine design developed in the systems engineering task, section 3.2.2.1. Task 203 from Mil-Std-1543B shall be accomplished for the turbopump except the sentence in paragraph 203.2.1 "This prediction shall include alternate missions and modes of operation" is deleted. The results from Task 203 shall be reported in contractor format in CDRL A007. The contractor shall conduct an integration task to insure the oxygen turbopump design is compatible with the oxygen and hydrogen preburners and the hydrogen turbopump.. The turbopump shall be designed to demonstrate the technologies incorporated into the preliminary engine design. The contractor shall identify areas of technical risk and conduct analyses and tests as necessary to reduce the risk to an acceptable level. Material and component testing shall be conducted wherever a sufficient data base does not exist to support the design. Alternative approaches shall be developed for areas that pose a significant cost or schedule risk to the contract.

Upon completion of the design, the contractor shall conduct a design review documenting material selection, verification tests and the design analyses. The contractor shall obtain written Government PCO approval of the detailed turbopump design before proceeding with turbopump fabrication. Informal design reviews may be held at times agreed to by the Government and the contractor. (A007/ Design Analysis Report, A009/Design Review Data Package, A011/Presentation Material, B002/Developmental Drawings)

The contractor shall identify and, upon written approval by the PCO, procure long-lead material items (items that must be purchased prior to completion and approval of the detailed design so as not to impact schedule). Following Government approval of the oxygen turbopump design, the contractor shall fabricate and assemble two complete turbopumps as well as procure long-lead material for a third turbopump. The contractor shall conduct tests on the assembled turbopump to verify the turbopump is ready for component tests. The turbopumps shall be transported by the contractor to Area 1-120 at the Phillips Laboratory, Edwards AFB for testing. (A010/ Long Lead Items List, A012/Still Photography Coverage, A013/ Test Plan,
A015/ Video Data, B002/Developmental Drawings)

Test Support

The contractor shall provide engineering and technical support for the oxygen turbopump component and integrated tests using the oxygen turbopump. The contractor shall develop a test plan for component level and integrated testing. The test plan shall as a minimum consist of: checkout/ spin tests, critical speed mapping, minimum Net Positive Section Head (NPSH)
mapping, and Head/Flow (H/Q) mapping. The test support shall consist of test planning; engineering and mechanical support to assure that facility interfaces meet the turbopump, preburner, and special test equipment requirements; test data analyses and interpretation; and post-test inspection of the oxygen turbopump. Control, red-line, and health management functions will be performed by the facility data acquisition and control system. The contractor shall document hazards to personnel and facilities associated with oxygen turbopump test operations, including component installation and tests. The contractor shall use MIL-STD-882C asa guide to prioritze hazards and determine an acceptable level of risk. The contractor shall document the hazards and necessary mitigating actions in the test plan. (A013/ Test Plan)

To support the integrated tests the contractor shall provide and integrate special test equipment which may consist of an oxygen turbopump turbine bypass control valve, a pump discharge control valve, and a heat exchanger, if necessary, to heat the oxygen discharged from the turbopump using the turbine discharge gases. A suggested configuration of the integrated powerhead demonstration is shown schematically in Figure 5.

Oxygen Preburner

The contractor shall design an oxidizer-rich preburner, capable of driving the oxygen turbopump turbine. The preburner design shall be sized to a nominal 250 klb engine vacuum thrust level. The

preburner shall be designed to demonstrate the technologies incorporated into the preliminary engine design developed in the systems engineering task, section 3.2.2.1.
Task 203 from Mil-Std-1543B shall be accomplished for the preburner except the sentence in paragraph 203.2.1 "This prediction shall include alternate missions and modes of operation" is deleted. The results from Task 203 shall be reported in contractor format in CDRL A007. The contractor shall conduct an integration task to insure the oxygen preburner design is compatible with the oxygen and hydrogen turbopumps and the hydrogen preburner.. The preburner shall be designed to demonstrate the technologies incorporated into the preliminary engine design. The contractor shall identify areas of technical risk and conduct analyses and tests as necessary to reduce the risk to an acceptable level. Material and component testing shall be conducted wherever a sufficient data base does not exist to support the design. Alternative approaches shall be developed for areas that pose a significant cost or schedule risk to the contract. Upon completion of the design, the contractor shall conduct a design review documenting material
selection, verification tests and the design analyses. The contractor shall obtain written Government PCO approval of the detailed preburner design before proceeding with preburner fabrication. Informal design reviews may be held at times agreed to by the Government and the contractor. (A007/ Design Analysis Report, A009/Design Review Data Package, A011/Presentation Material, B002/Developmental Drawings)

The contractor shall identify and, upon written approval by the PCO, procure long-lead material items (items that must be purchased prior to completion and approval of the detailed design so as not to impact the schedule). Following Government approval of the oxygen preburner design, the contractor shall fabricate and assemble two complete preburners as well as procure long-lead material for a third preburner. The contractor shall conduct tests on the assembled preburner to verify the preburner is ready for component tests. The preburners shall be transported by the contractor to Area 1-120 at the Phillips Laboratory, Edwards AFB for testing. (A010/ Long Lead Items List, A012/Still Photography Coverage, A013/ Test Plan,
A015/ Video Data, B002/Developmental Drawings)

Test Support

The contractor shall provide engineering and technical support for the oxygen preburner component and integrated tests using the oxidizer-rich preburner. The contractor shall develop a test plan for component level and integrated testing. The test plan shall as a minimum consist of: ignition tests, stability tests, mixing uniformity verification, and mixture ratio excursions over the operating range. The test support shall consist of test planning; engineering and mechanical support to assure that facility interfaces meet the turbopump, preburner, and special test equipment requirements; test data analyses and interpretation; and post-test

inspection of the oxidizer-rich preburner . Control, red-line, and health management functions will be performed by the facility data acquisition and control system. The contractor shall document hazards to personnel and facilities associated with oxidizer-rich preburner test operations, including component installation and tests. The contractor shall use
MIL-STD-882C as a guide to prioritze hazards and determine an acceptable level of risk. The contractor shall document the hazards and necessary mitigating actions in the test plan. (A013/ Test Plan)

The contractor shall provide and integrate special test equipment which may consist of preburner inlet control valves. A suggested configuration of the integrated powerhead demonstration is shown schematically in Figure 5.

Hydrogen Turbopump

The contractor shall design a hydrogen turbopump. The turbopump design shall be sized to a nominal 250 klb engine vacuum thrust level. The turbopump shall be designed to demonstrate the technologies incorporated into the preliminary engine design developed in the systems engineering task. Task 203 from Mil-Std-1543B shall be accomplished for the turbopump except the sentence in paragraph 203.2.1 "This prediction shall include alternate missions and modes of operation" is deleted. The results from Task 203 shall be reported in contractor format in CDRL A007. The contractor shall conduct an integration task to insure the hydrogen turbopump design is compatible with the oxygen and hydrogen preburners and the oxygen turbopump. The turbopump shall be designed to demonstrate the technologies incorporated into the preliminary engine design. The contractor shall identify areas of technical risk and conduct analyses and tests as necessary to reduce the risk to an acceptable level. Material and component testing shall be conducted wherever a sufficient data base does not exist to support the design. Alternative approaches shall be developed for areas that pose a significant cost or schedule risk to the contract. Upon completion of the design, the contractor shall conduct a design review documenting material selection, verification tests and the design analyses.
The contractor shall obtain written Government PCO approval of the detailed turbopump design before proceeding with turbopump fabrication. Informal design reviews may be held at times agreed to by the Government and the contractor. (A007/ Design Analysis Report, A009/Design Review Data Package, A011/Presentation Material, B002/Developmental Drawings)

The contractor shall identify and, upon written approval by the PCO, procure long-lead material items (items that must be purchased prior to completion and approval of the detailed design so as not to impact the schedule). Following Government approval of the hydrogen turbopump design, the contractor shall fabricate and assemble two complete turbopumps as well
as procure long-lead material for a third turbopump. The contractor shall conduct tests on the assembled turbopump to verify the turbopump is ready for component tests. The turbopumps shall be

transported by the contractor to Area 1-120 at the Phillips Laboratory, Edwards AFB for testing. (A010/ Long Lead Items List, A012/Still Photography Coverage, A013/ Test Plan, A015/ Video Data, B002/Developmental Drawings)

Test Support

The contractor shall provide engineering and technical support for the hydrogen turbopump component and integrated tests using the hydrogen turbopump. The contractor shall develop a test plan for component level and integrated testing. The test plan shall as a minimum consist of: checkout/ spin tests, critical speed mapping, minimum NPSH mapping, and H/Q mapping. The test support shall consist of test planning; engineering and mechanical support to assure that facility interfaces meet the turbopump, preburner, and special test equipment requirements; test data analyses and interpretation; and post-test inspection of the hydrogen turbopump. Control, red-line, and health management functions will be performed by the facility data acquisition and control system. The contractor shall document hazards to personnel and facilities associated with hydrogen turbopump test operations, including component installation and tests. The contractor shall use MIL-STD-882C as a guide to prioritze hazards and determine an acceptable level of risk. The contractor shall document the hazards and necessary mitigating actions in the test plan. (A013/ Test Plan)

To support the integrated tests the contractor shall provide and integrate special test equipment which may consist of an hydrogen turbopump turbine bypass control valve, a pump discharge control valve, and a heat exchanger to heat the hydrogen discharged from the turbopump using the turbine discharge gases. A suggested configuration of the integrated powerhead demonstration is shown schematically in Figure 5.

Hydrogen Preburner

The contractor shall design a hydrogen rich preburner. The preburner design shall be sized to a nominal 250 klb engine vacuum thrust level. The preburner shall be designed to demonstrate the technologies incorporated into the preliminary engine design developed in the systems engineering task, section 3.2.2.1. Task 203 from Mil-Std-1543B shall be accomplished for the preburner except the sentence in paragraph 203.2.1 "This prediction shall include alternate missions and modes of operation" is deleted. The results from Task 203 shall be reported in contractor format in CDRL A007. The contractor shall conduct an integration task to insure the hydrogen preburner design is compatible with the oxygen and hydrogen turbopumps and
oxygen turbopump. The preburner shall be designed to demonstrate the technologies incorporated into the preliminary engine design. The contractor shall identify areas of technical risk and conduct analyses and tests as necessary to reduce the risk to an acceptable level. Material and component testing shall be conducted wherever a sufficient data base does

not exist to support the design. Alternative approaches shall be developed for areas that pose a significant cost or schedule risk to the contract. Upon completion of the design, the contractor shall conduct a design review documenting material selection, verification tests and the design analyses. The contractor shall obtain written Government PCO approval of the detailed preburner design before proceeding with preburner fabrication. Informal design reviews may be held at times agreed to by the Government and the contractor. (A007/ Design Analysis Report, A009/Design Review Data Package, A011/Presentation Material, B002/Developmental Drawings)

The contractor shall identify and, upon written approval by the PCO, procure long-lead material items (items that must be purchased prior to completion and approval of the detailed design so as not to impact the schedule). Following Government approval of the hydrogen preburner design, the contractor shall fabricate and assemble two complete preburners as well as procure long-lead material for a third preburner. The contractor shall conduct tests on the assembled preburner to verify the preburner is ready for component tests. The preburners shall be transported by the contractor to Area 1-120 at the Phillips Laboratory, Edwards AFB for testing. (A010/ Long Lead Items List, A012/Still Photography Coverage, A013/ Test Plan, A015/ Video Data, B002/Developmental Drawings)

Test Support

The contractor shall provide engineering and technical support for the hydrogen preburner component and integrated tests using the hydrogen rich preburner. The contractor shall develop a test plan for component level and integrated testing. The test plan shall as a minimum consist of: ignition tests, stability tests, mixing uniformity verification, and mixture ratio excursions over the operating range. The test support shall consist of test planning; engineering and mechanical support to assure that facility interfaces meet the turbopump, preburner, and special test equipment requirements; test data analyses and interpretation; and post-test inspection of the hydrogen-rich preburner. Control, red-line, and health management functions will be performed by the facility data acquisition and control system. The contractor shall document hazards to personnel and facilities associated with hydrogen-rich preburner test operations, including component installation and tests. The contractor shall use MIL-STD-882C as a guide to prioritze hazards and determine an acceptable level of risk. The contractor shall document the hazards and necessary mitigating actions in the test plan. (A013/ Test Plan)

The contractor shall provide and integrate special test equipment which may consist of preburner inlet control valves.

The contractor shall provide technical and financial data per the Contract Data Requirements List, Exhibit A and B to the contract.

3.8 Additional Documents: The following documents are not mandatory, but may be useful in the performance of this effort.

NPRD-91	Nonelectronic Parts Reliability Data, 01 May 91 Reliability Analysis Center, Rome Air Development Center, Griffiss AFB, NY (315) 377-0900
Mil-HDBK-217	Reliability Prediction of Electronic Equipment, 10 Jul 92
AFWAL-TR-83-2079	Weibull Analysis Handbook, Nov 83

RELIABILITY GOALS

Probability of Mission Loss due to Propulsion 1/400
Probability of Vehicle Loss due to Propulsion 1/4000

LIFE GOALS

Life of major components >100 missions, 400 missions desired

VEHICLE PERFORMANCE

Payload Performance to 100 Nautical Miles Polar 15 klb
Thrust-to-Weight at Liftoff With Engine Out >1.05
Vehicle Mass at Polar Insertion (excluding payload) <189 klb, 161 klb desired

PROPULSION SYSTEM CAPABILITY

Restart Capability Sea Level and Vacuum
Engine Throttle Range 5:1

MAINTENANCE GOALS

Mean Downtime compatible with 1 week vehicle mean downtime
Mean Time Between Overhaul >50 missions
Propulsion Maintenance Cost per Flight <$600 k
(includes all depot costs)

PROPULSION COST GOALS

Amortized Propulsion Systems Cost per Flight <$2M
(excluding development costs)